Phase Closure Nulling: Toward Detecting Exoplanets

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AMBER Task Force at Laboratoire d'Astrophysique de Grenoble (LAOG):
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JPL Exoplanet seminar - Oct 16, 2008

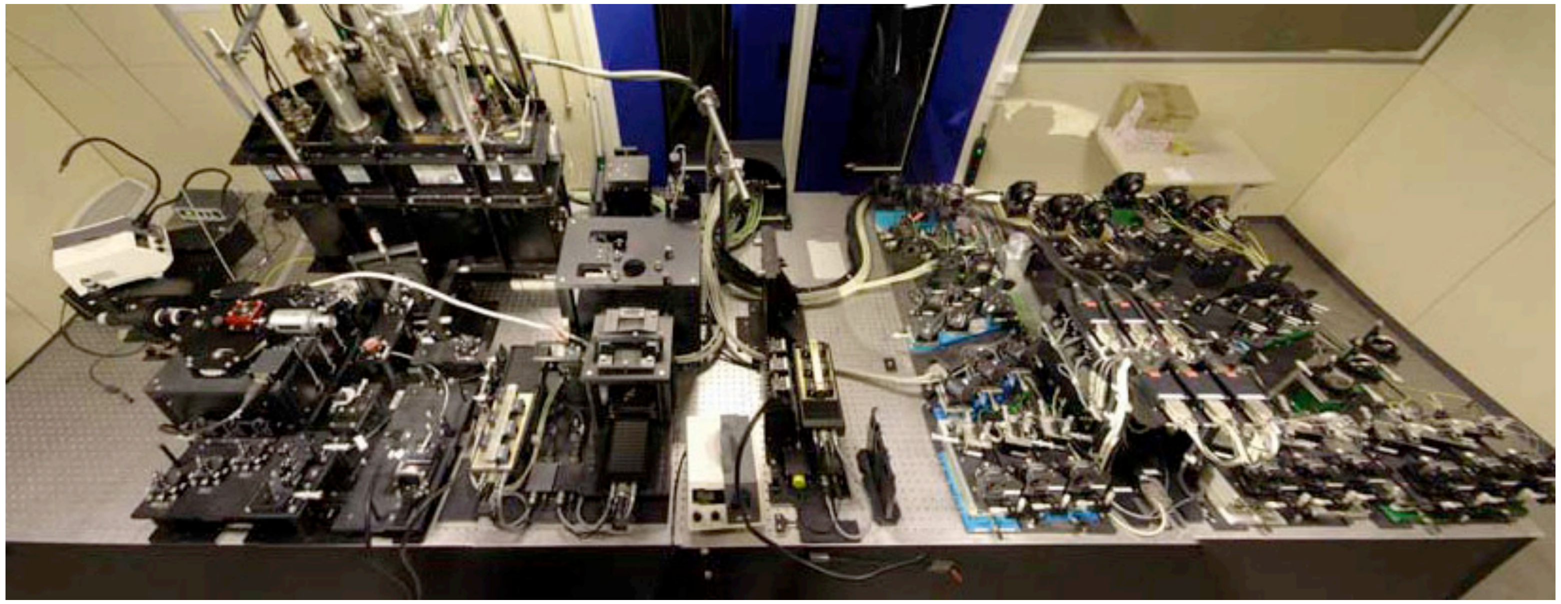
Outline

- AMBER observations on **σ Puppis**
- Some basics about interferometric measurements
- Phase closure and closure phases
- Phase closure nulling
- Toward detection of exoplanets
- Other possible applications

DISCLAIMER: Work in progress (two papers submitted).

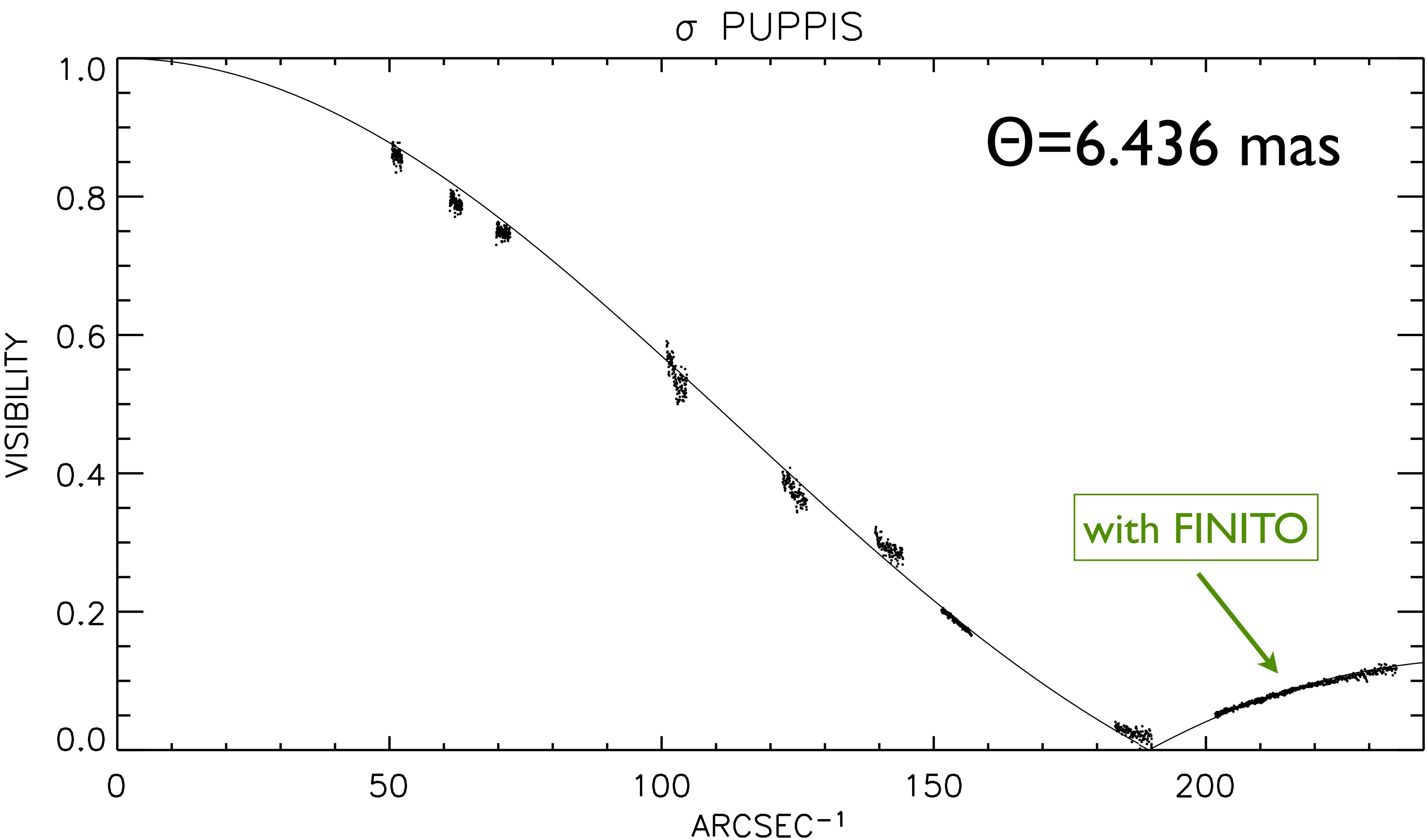
AMBER Task Force

To bring in contractual specifications, the accuracy of the absolute visibility, of the differential and of the closure phases through a fundamental analysis of the instrument status and limitations.

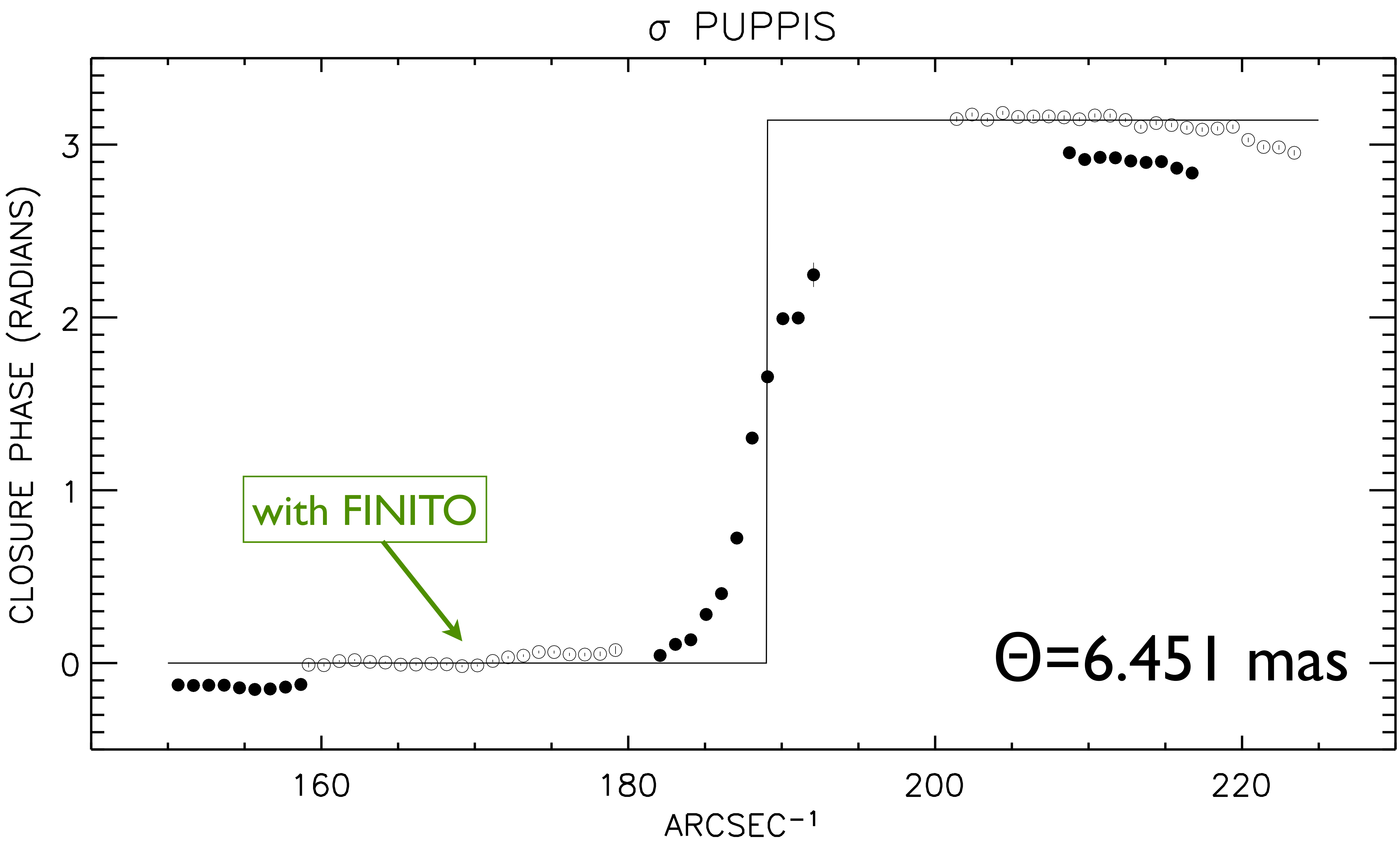


A run took place in Feb 2008 to solve this issue and...

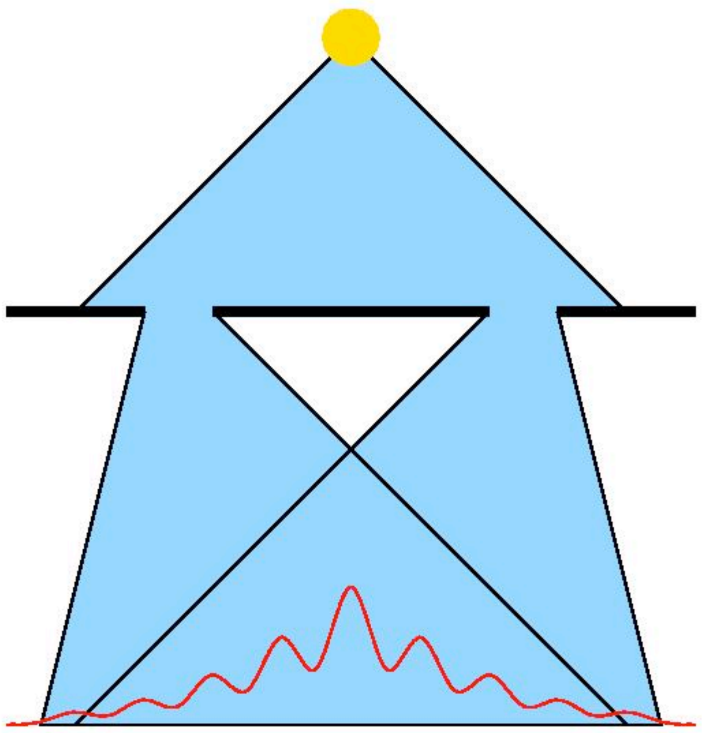
AMBER observations of σ Puppis

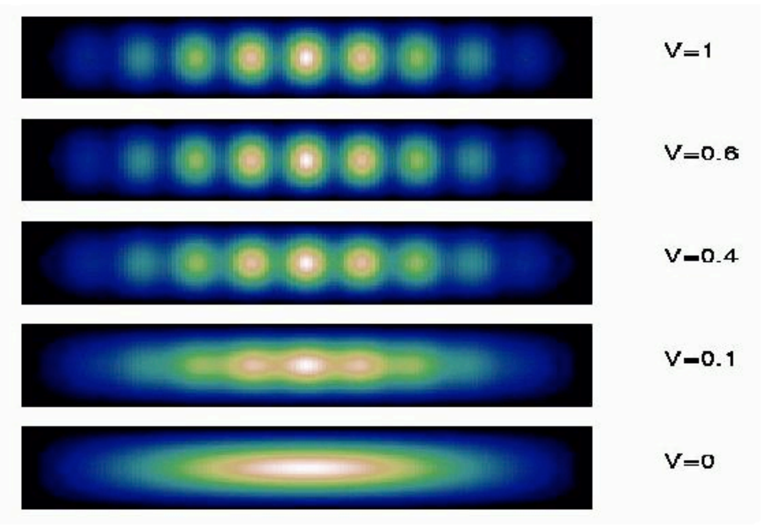


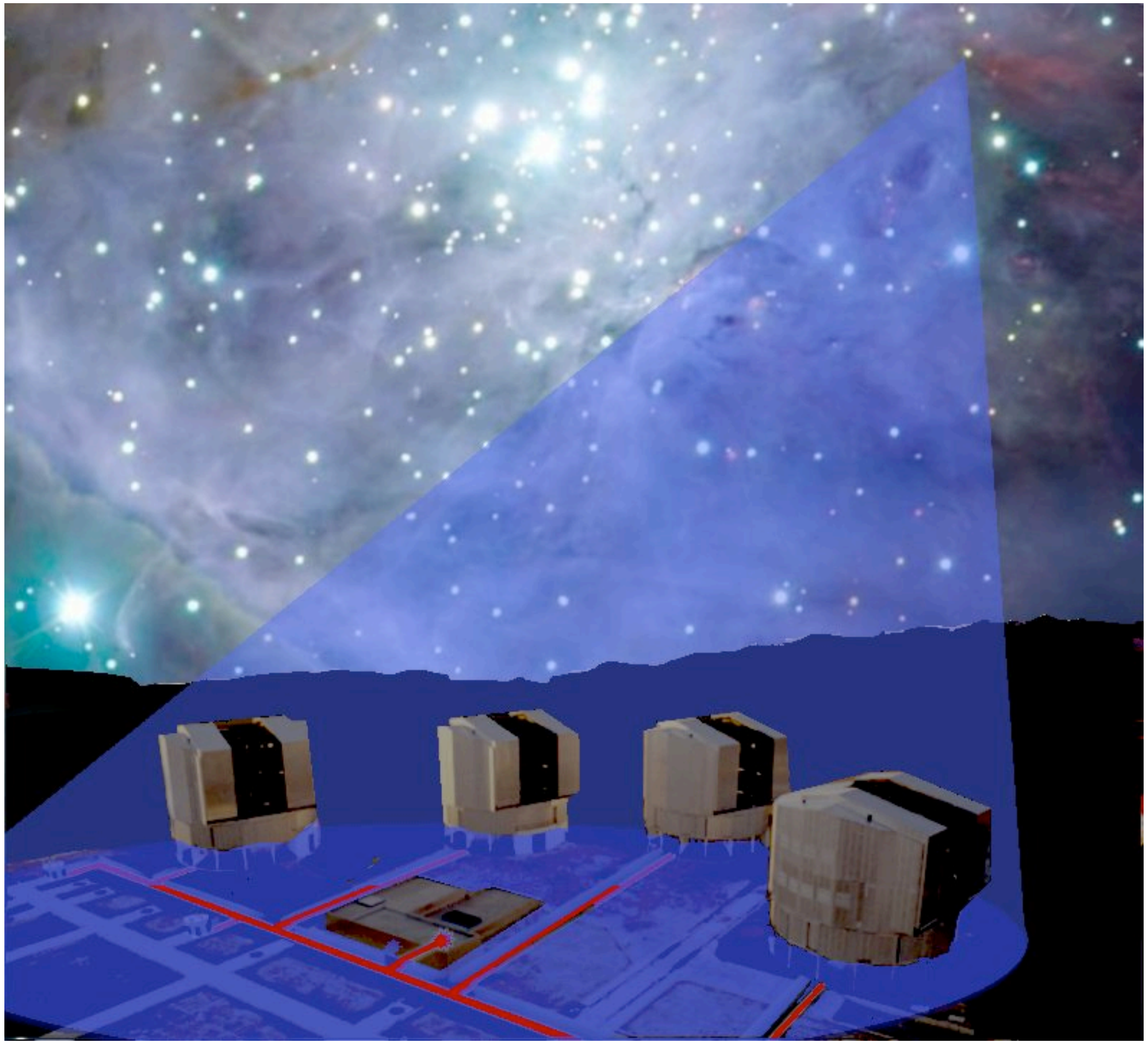
Closure phases on σ Puppis



Principle of interferometry







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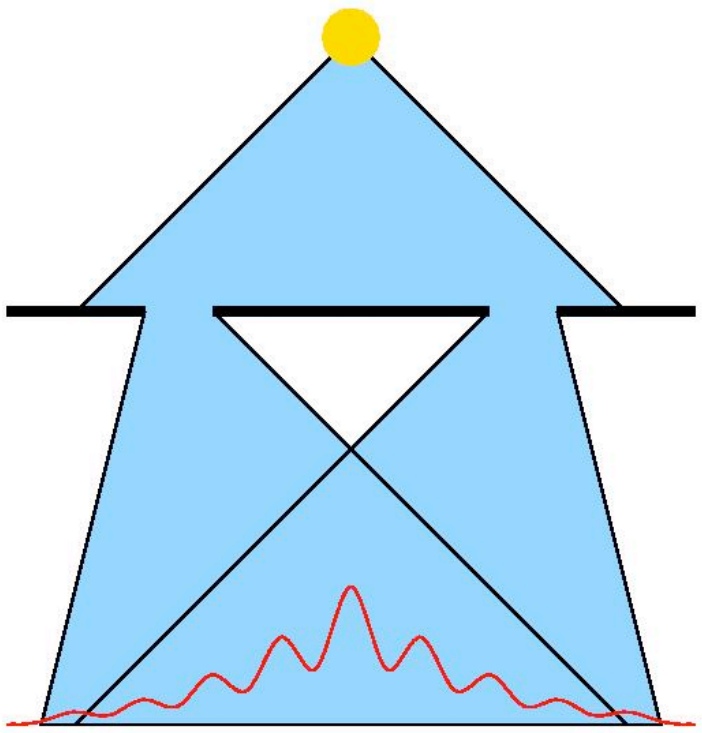
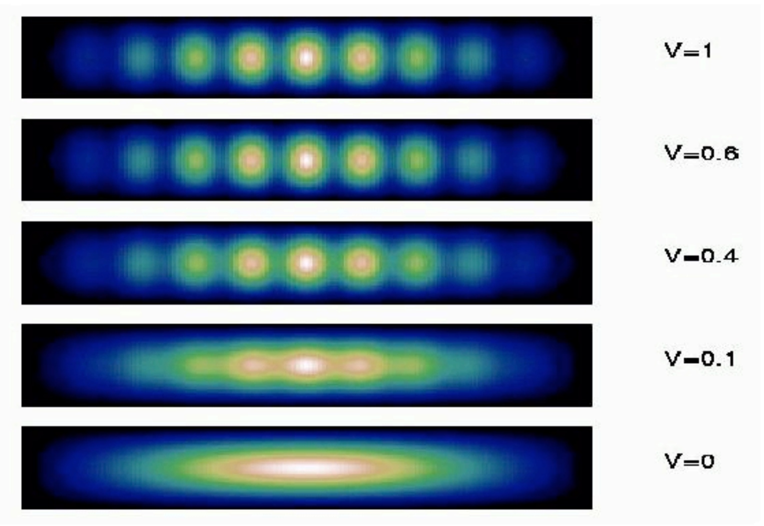
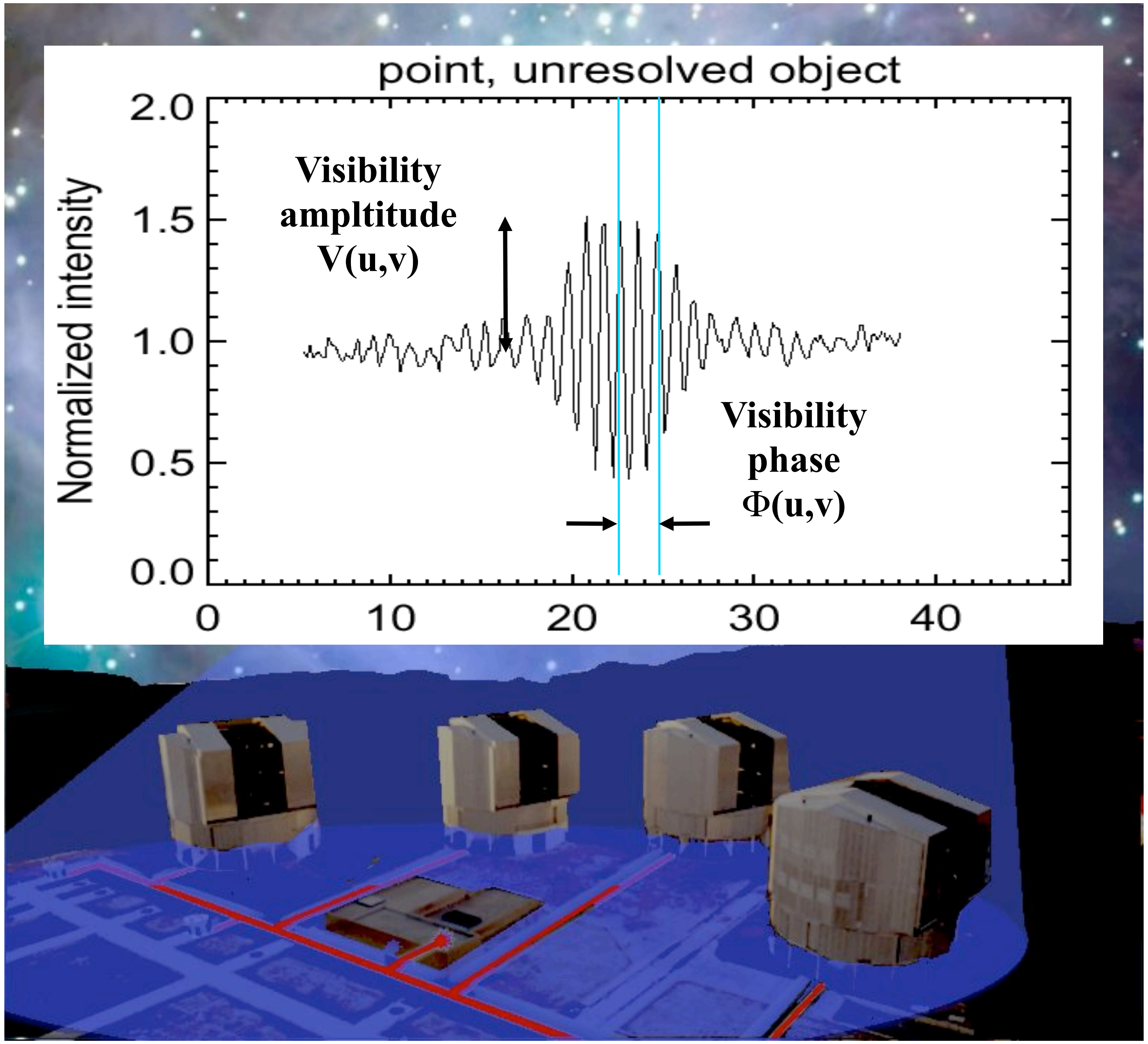
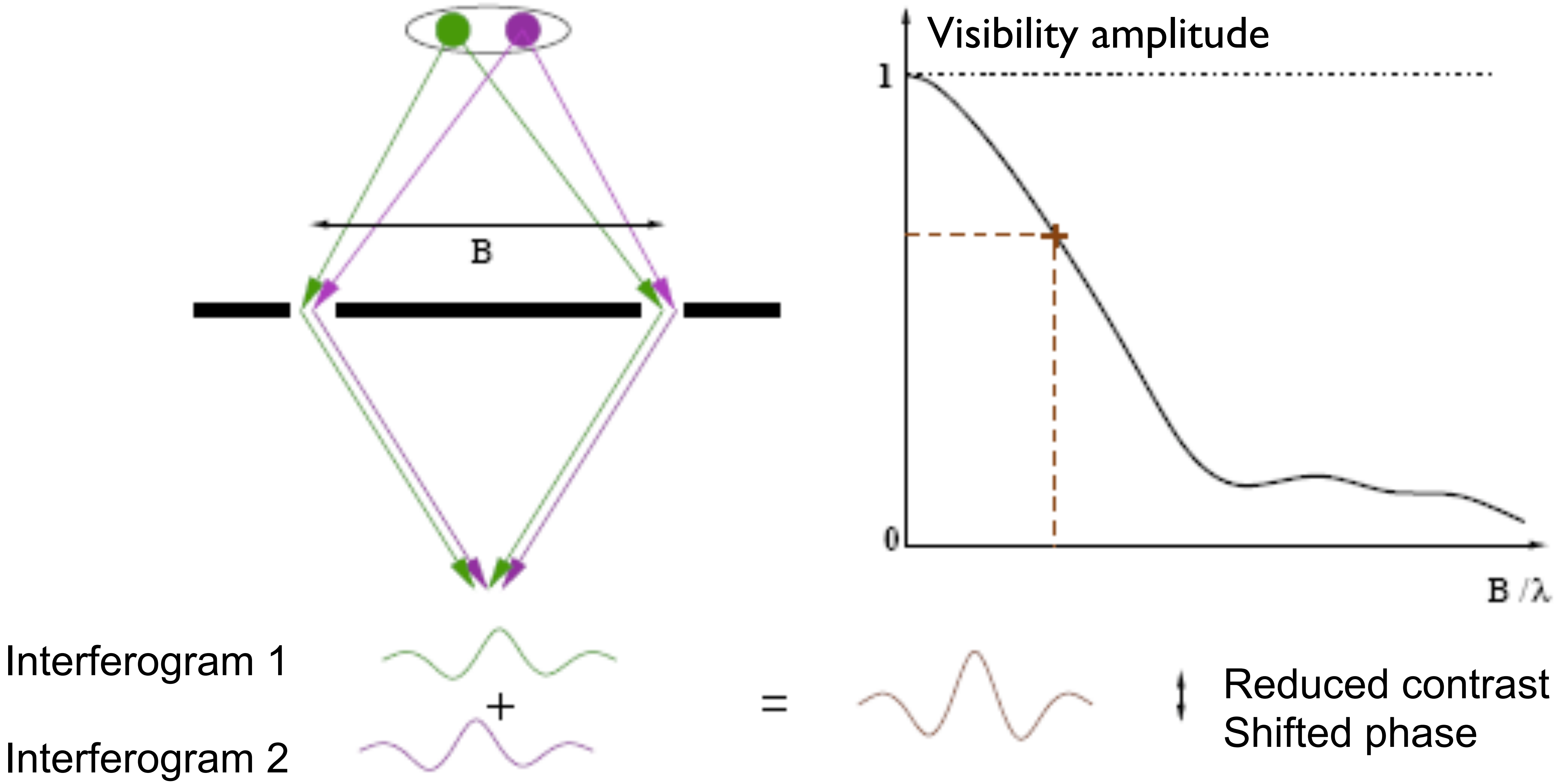






Spatial coherence

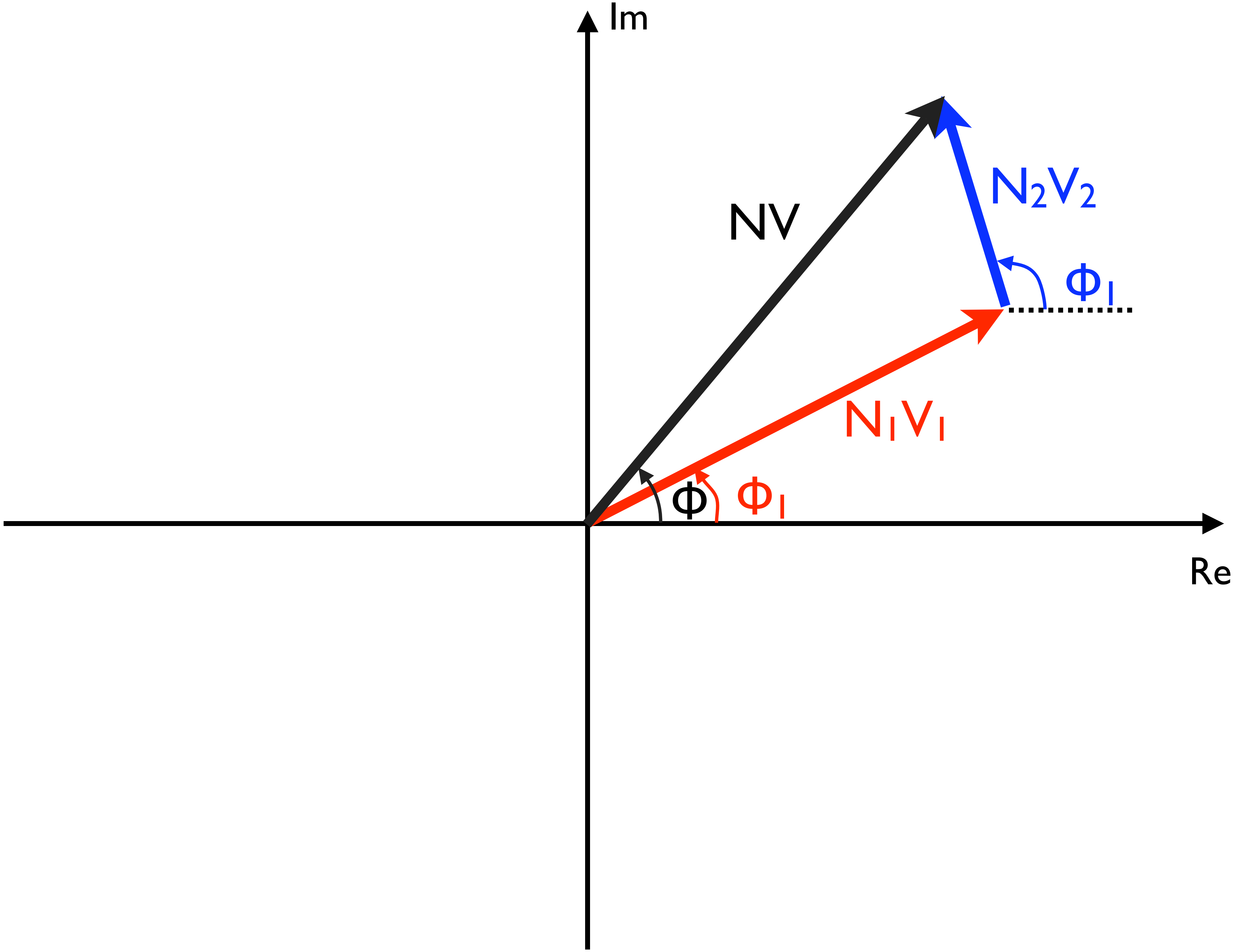


Zernicke-van Cittert theorem

Visibility = Fourier transform of the brightness spatial distribution

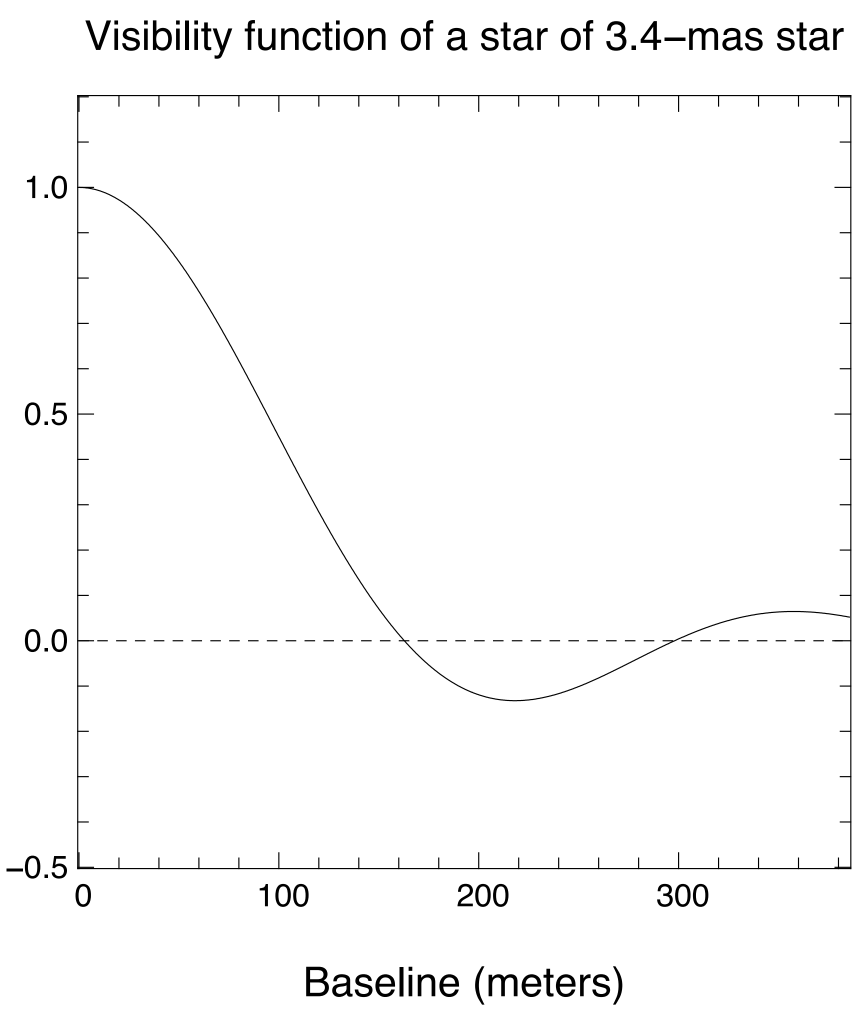
Complex coherent fluxes add, not just visibilities: $NVe^{j\Phi} = N_1V_1e^{j\Phi_1} + N_2V_2e^{j\Phi_2}$

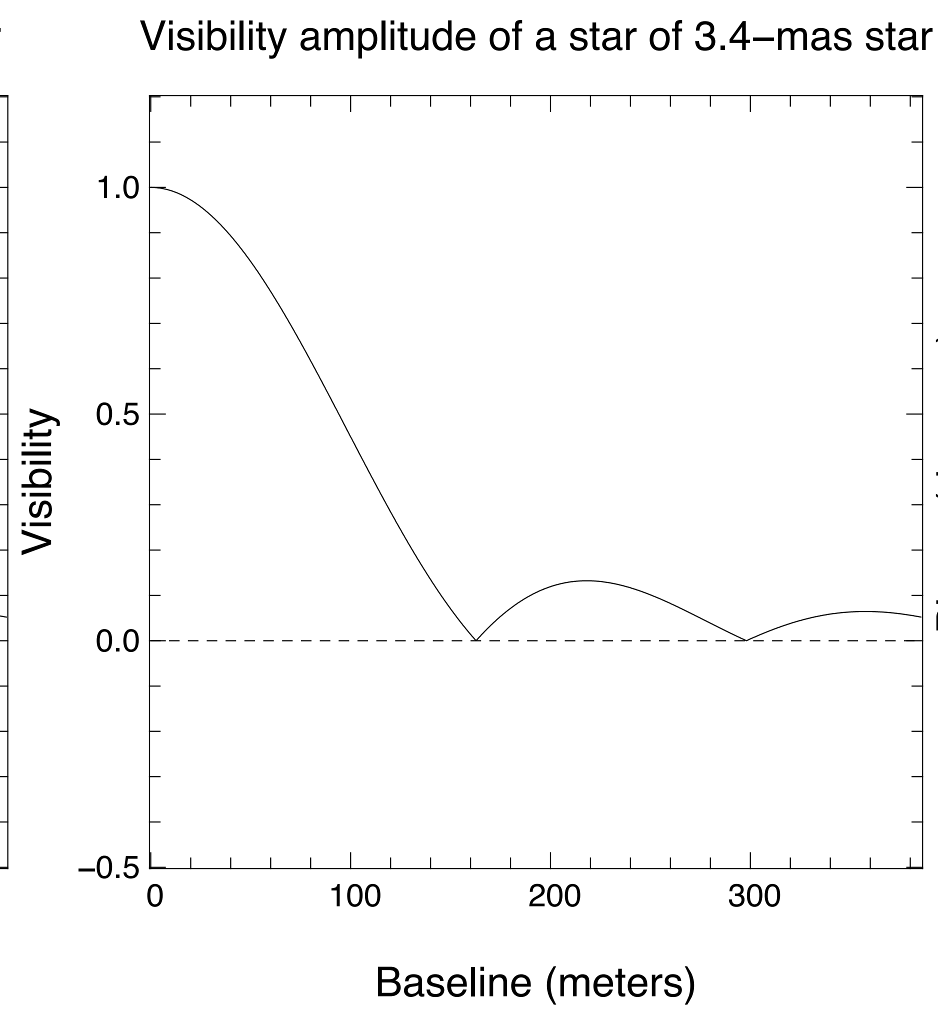
Fresnel vectors

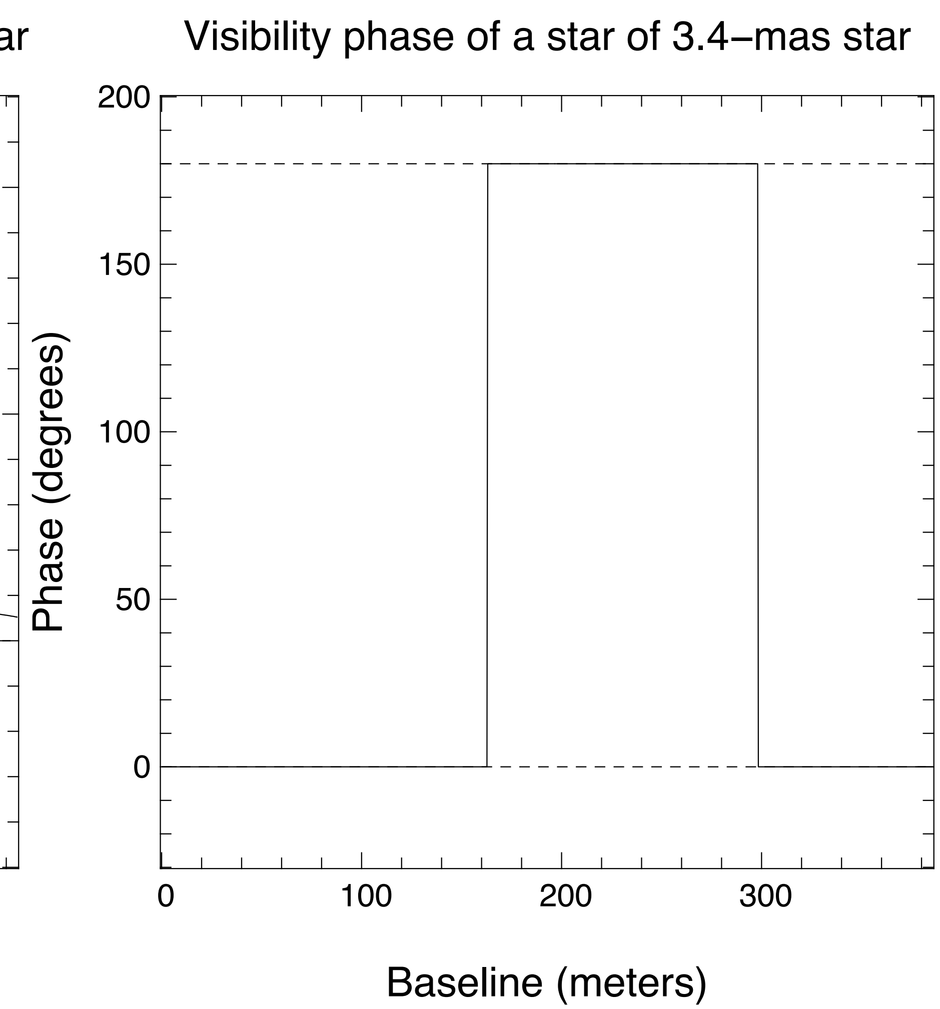


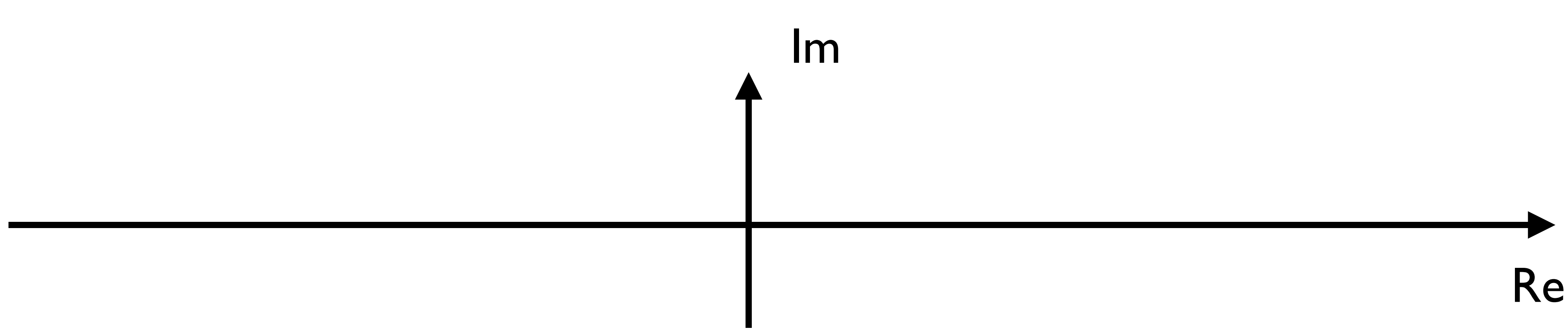
Complex visibility of a resolved star

$$V_\star(u) = 2\,\frac{J_1(2\pi\, u\, R_\star)}{2\pi\, u\, R_\star}.$$









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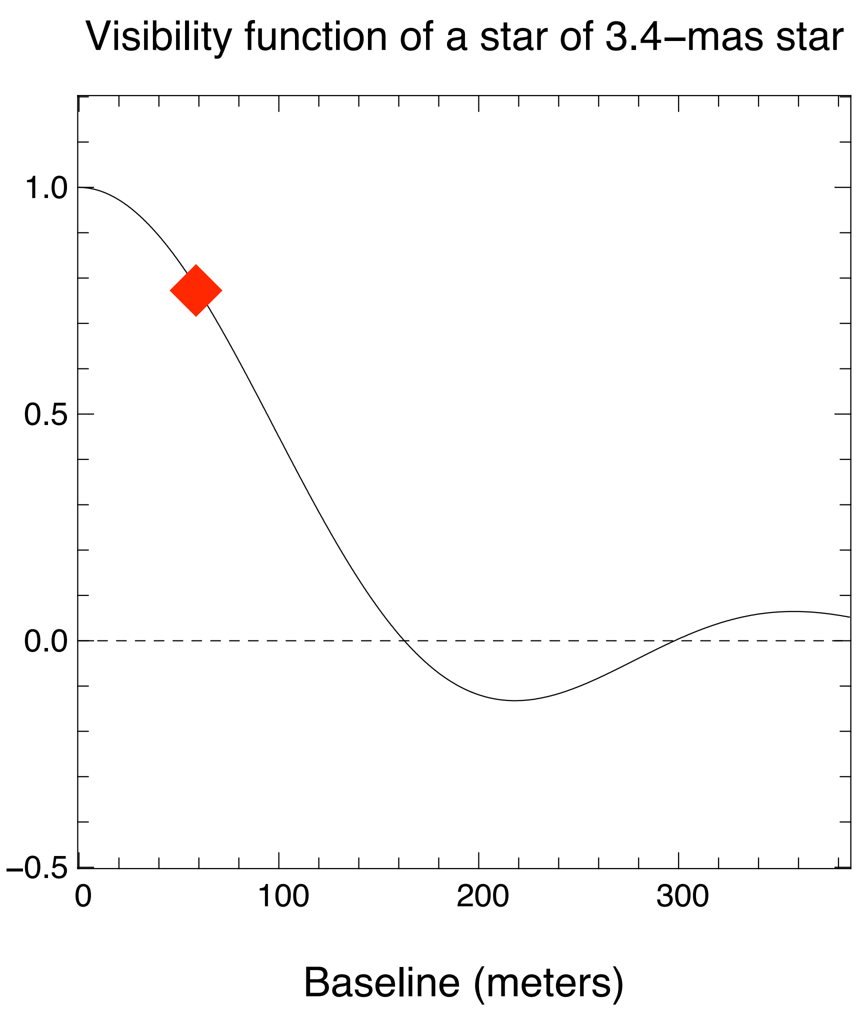

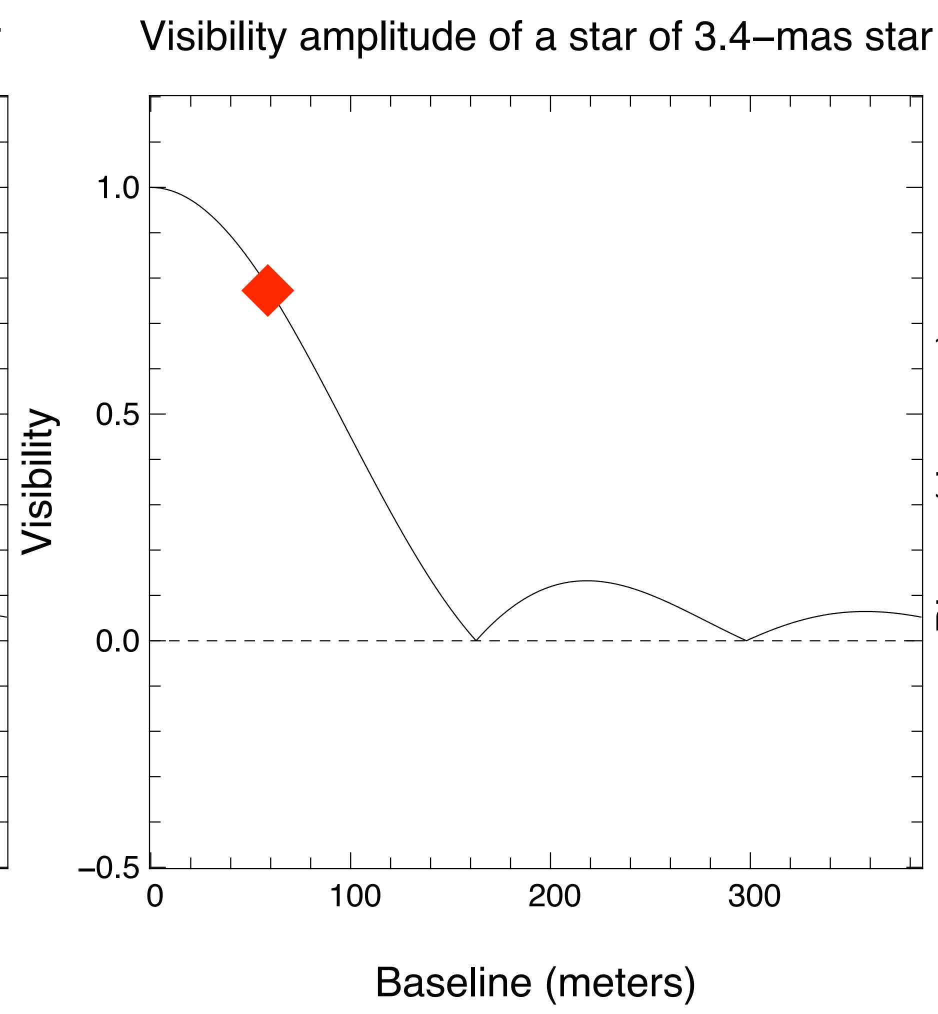

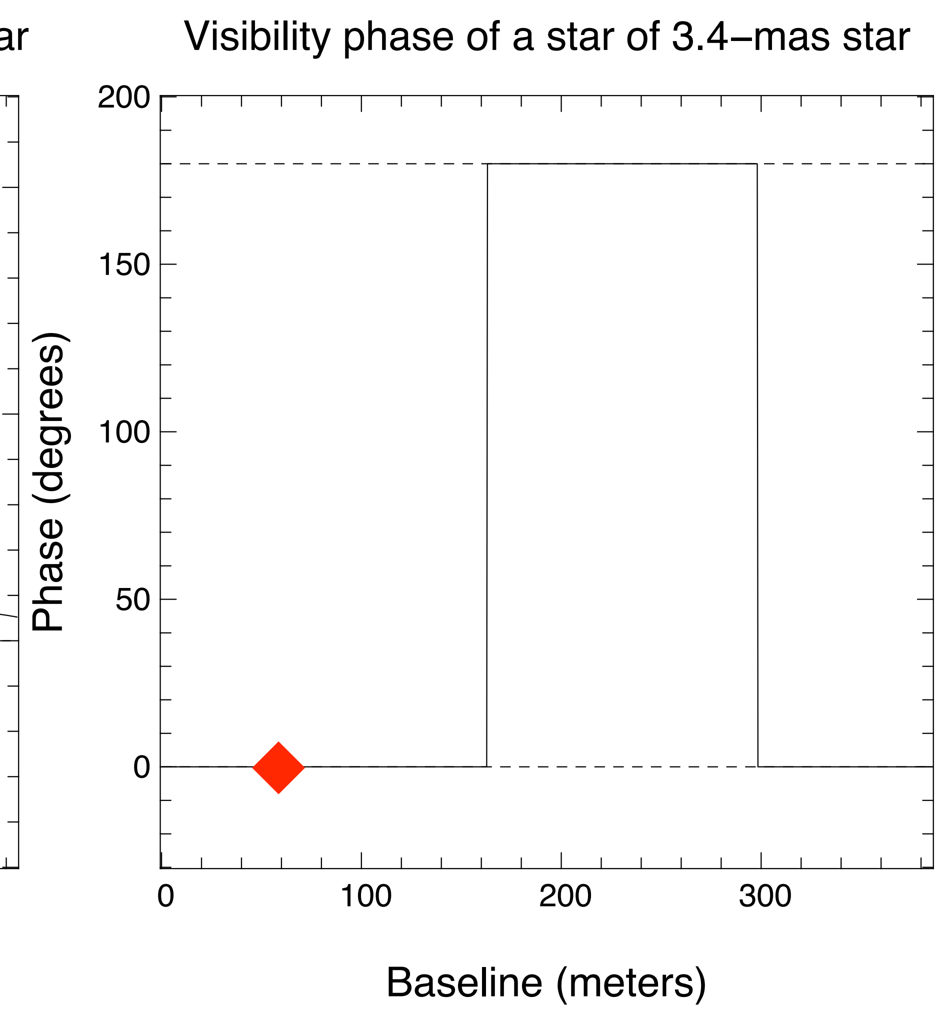

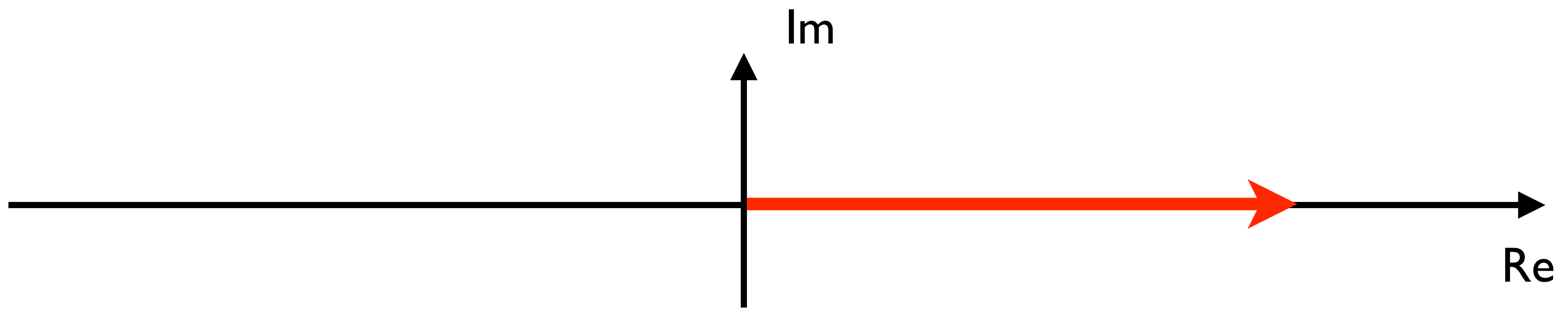

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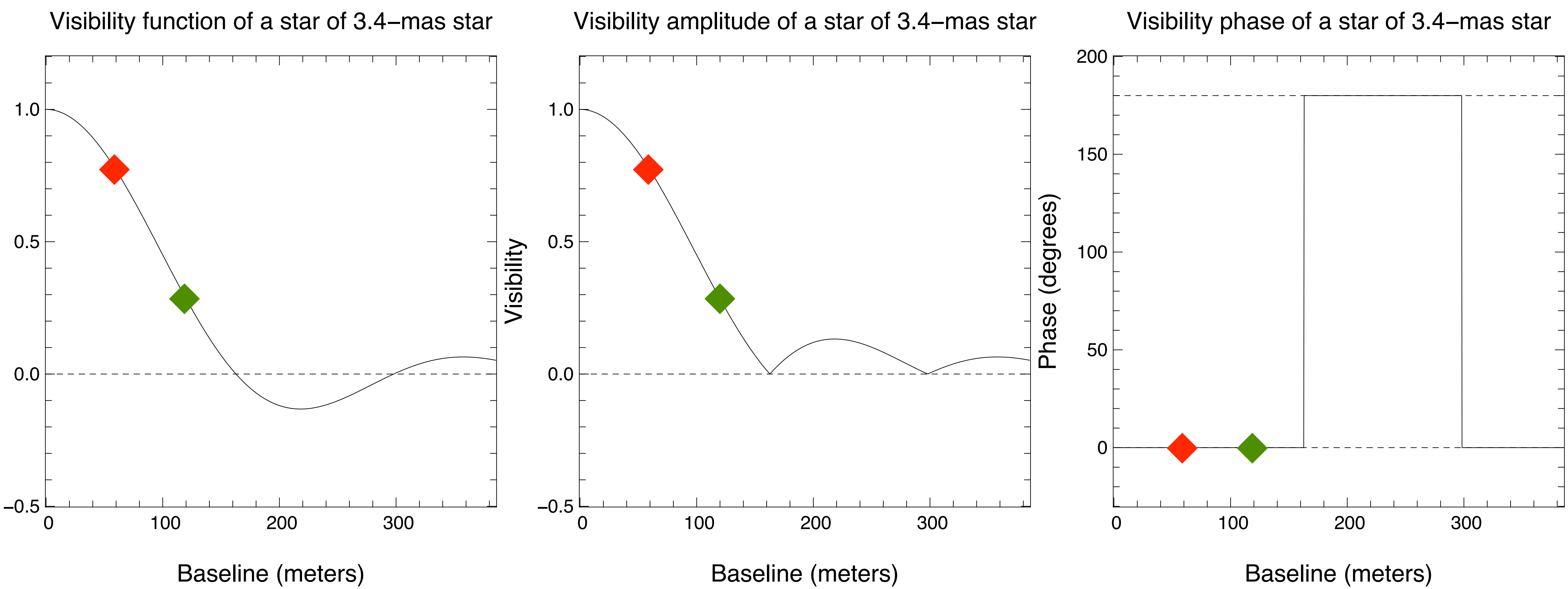

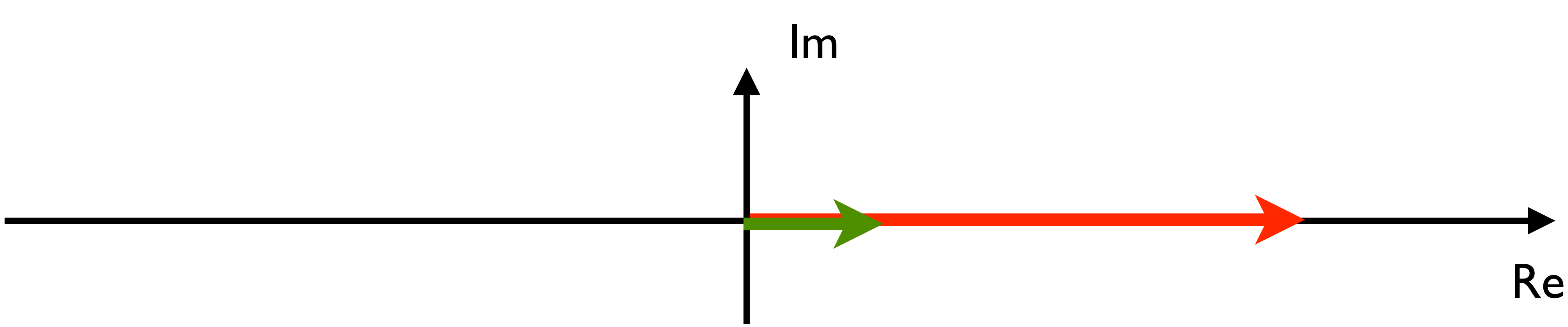

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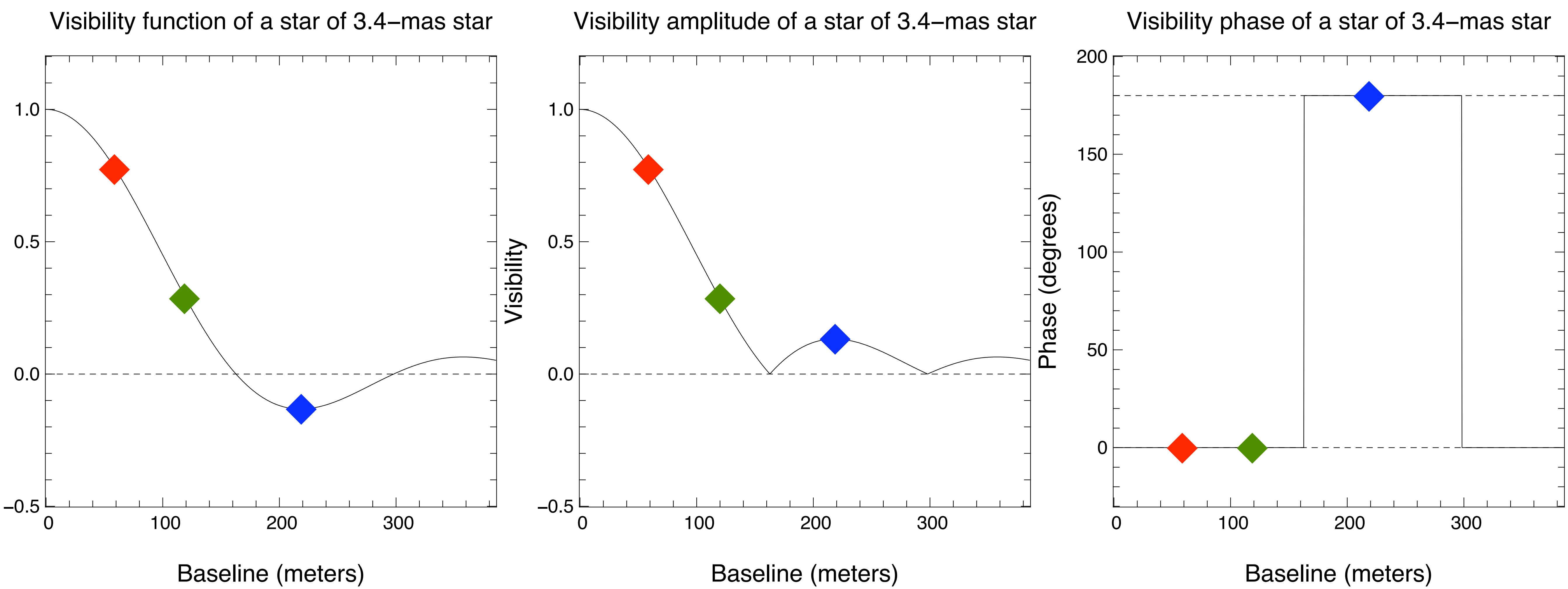
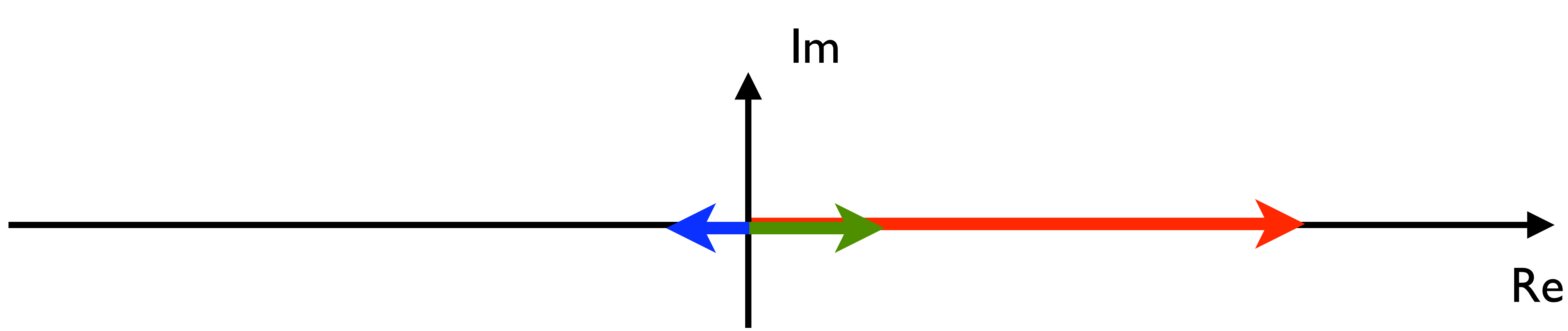
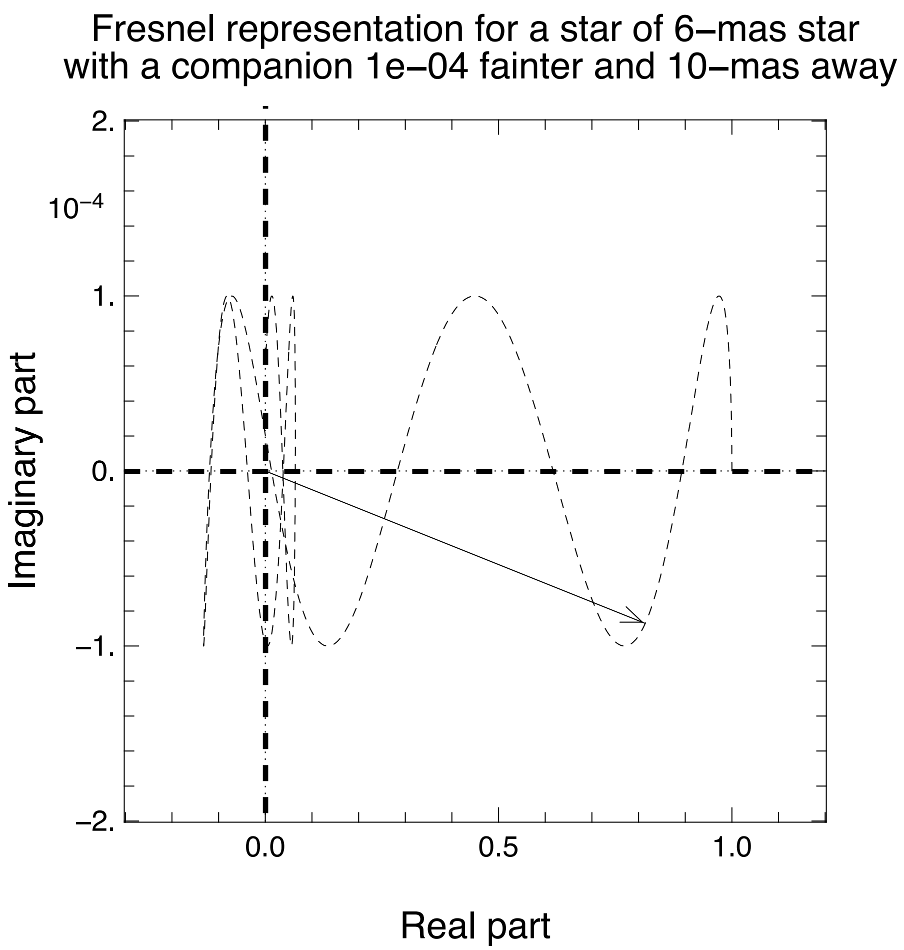
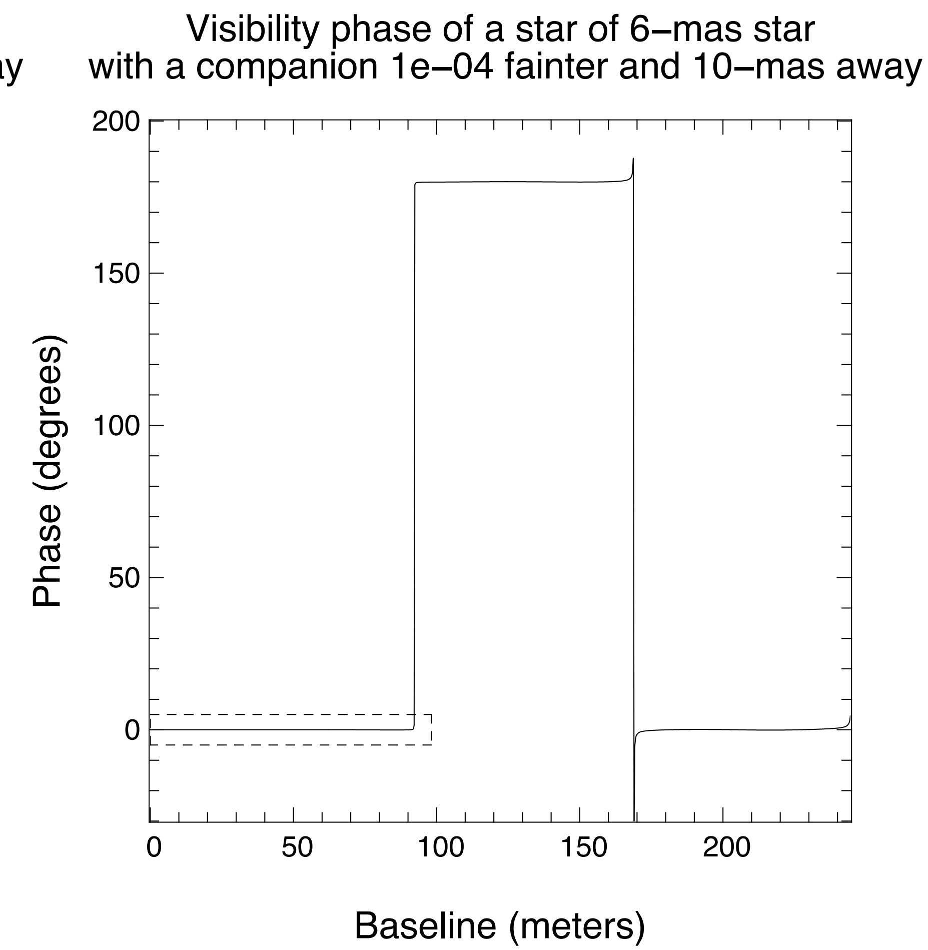


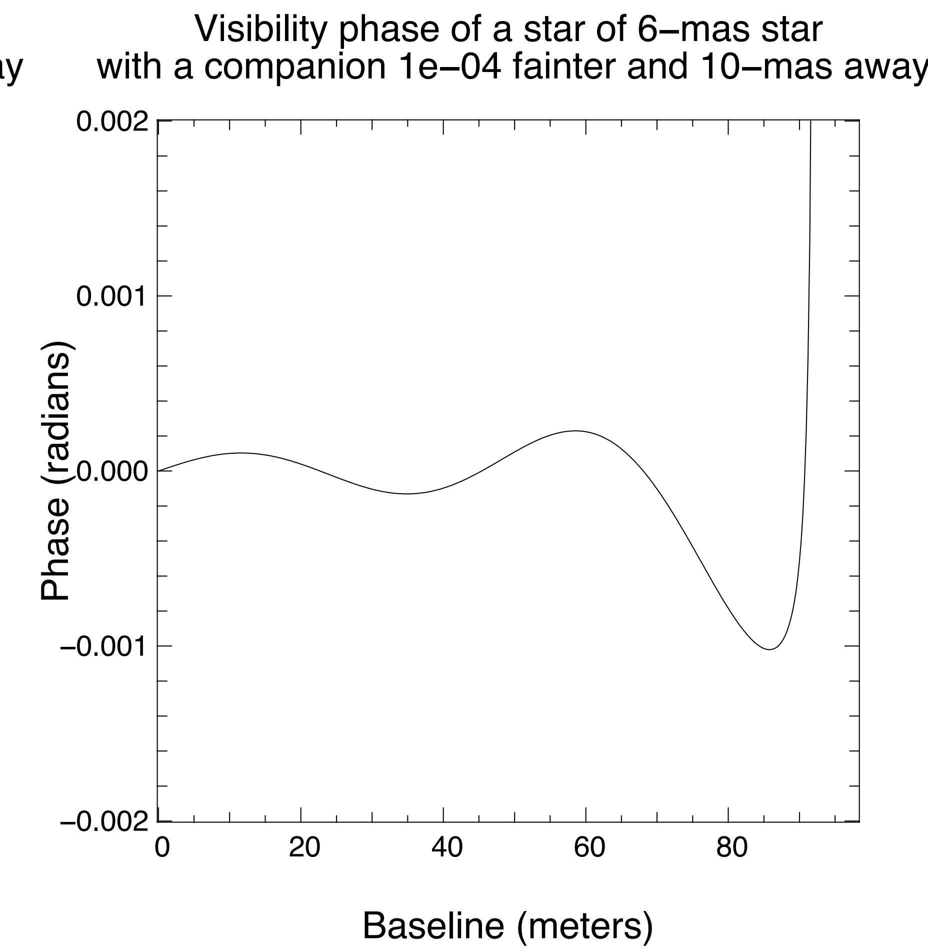


Complex visibility of a double system

$$\hat{\imath}(u) = \frac{V_\star(u) + r e^{i\,2\pi u s}}{1+r}$$







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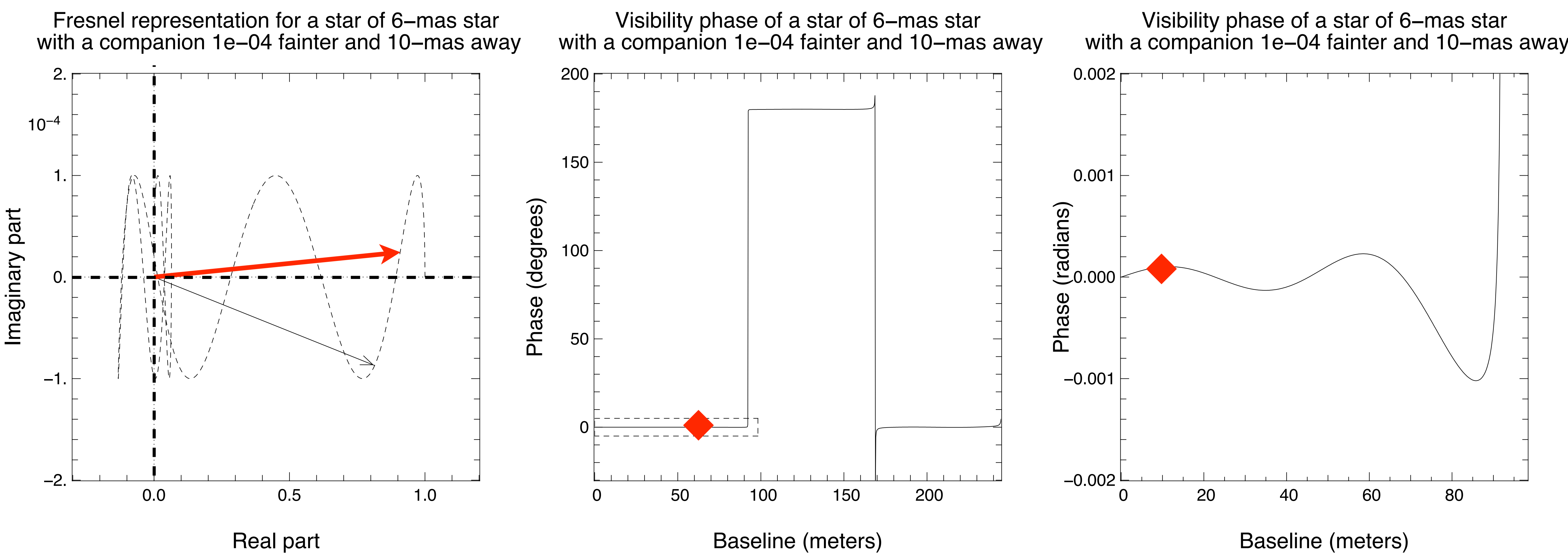

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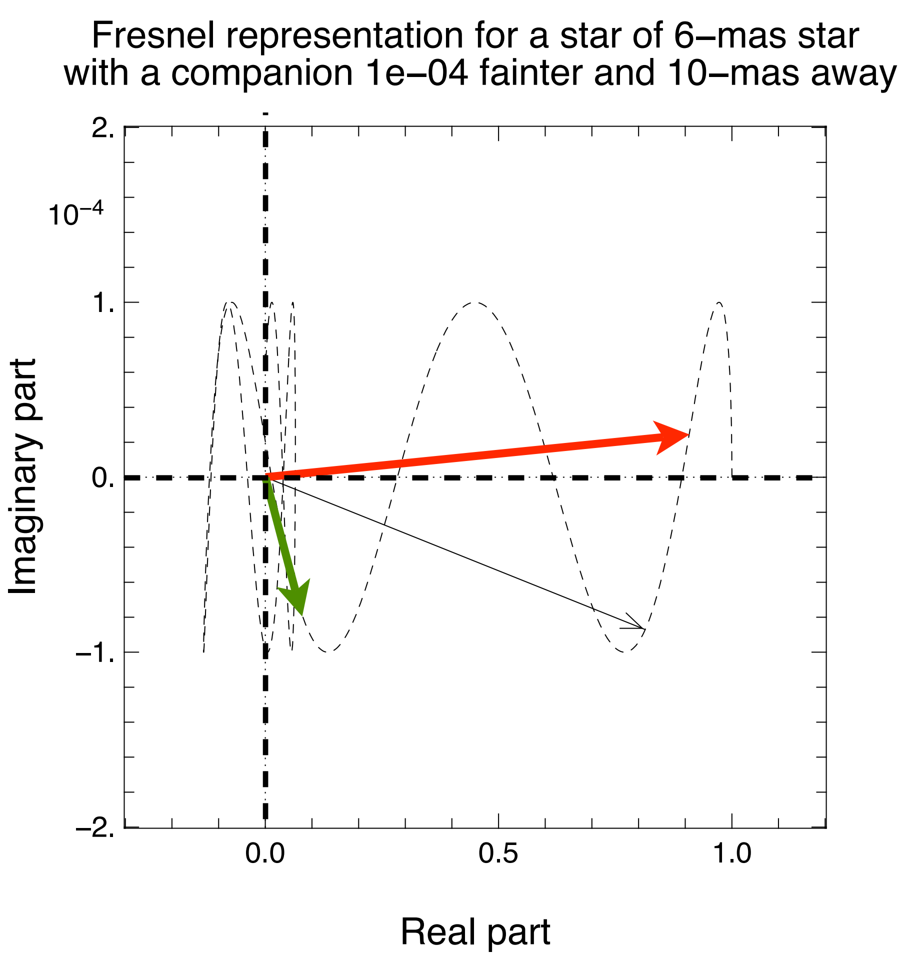

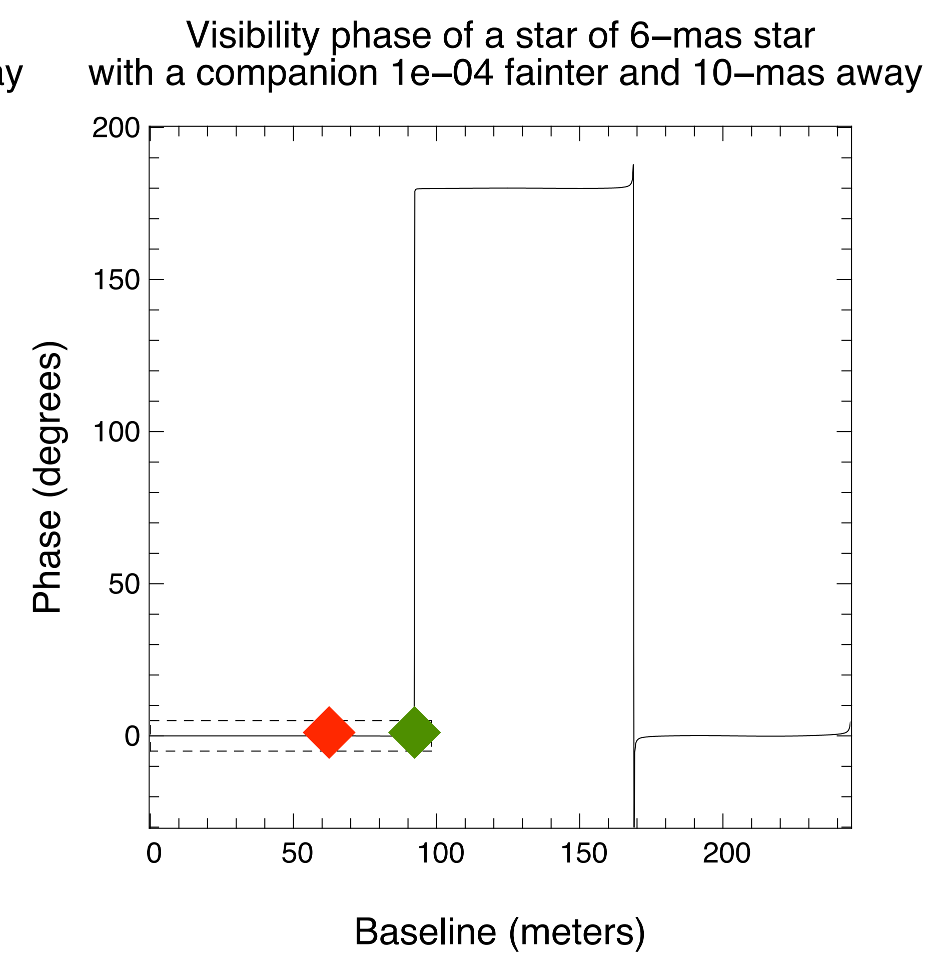

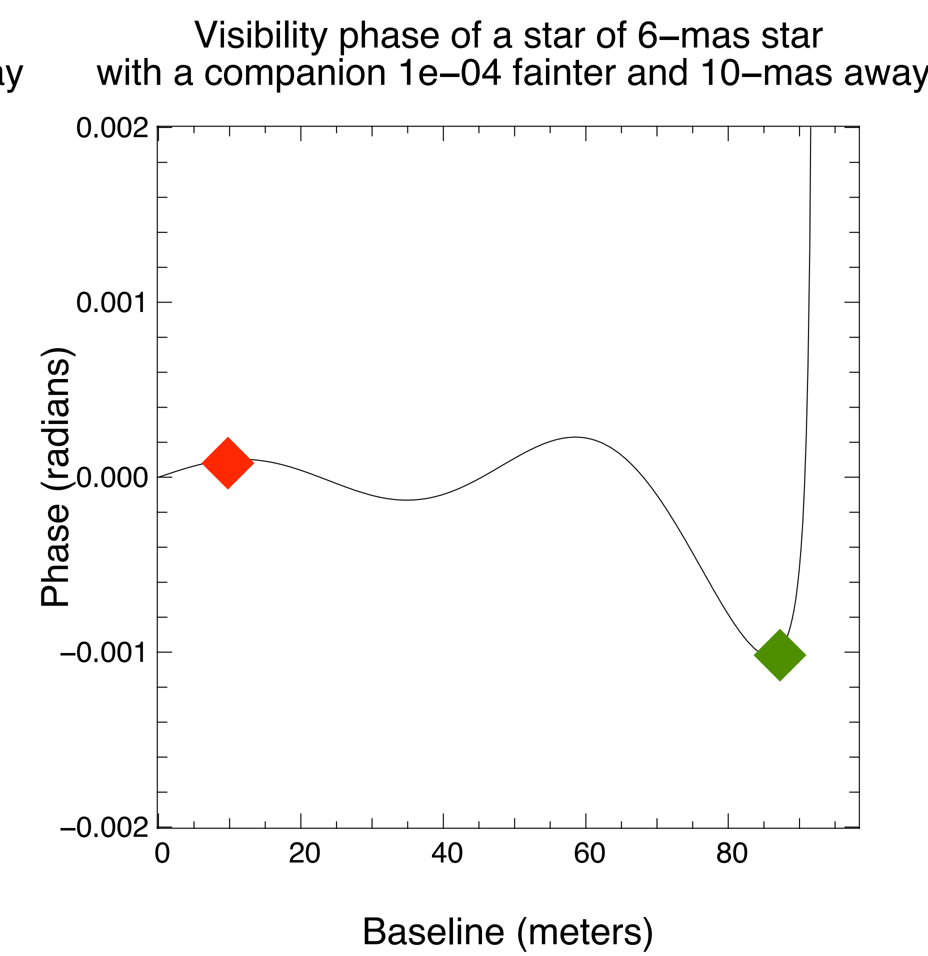

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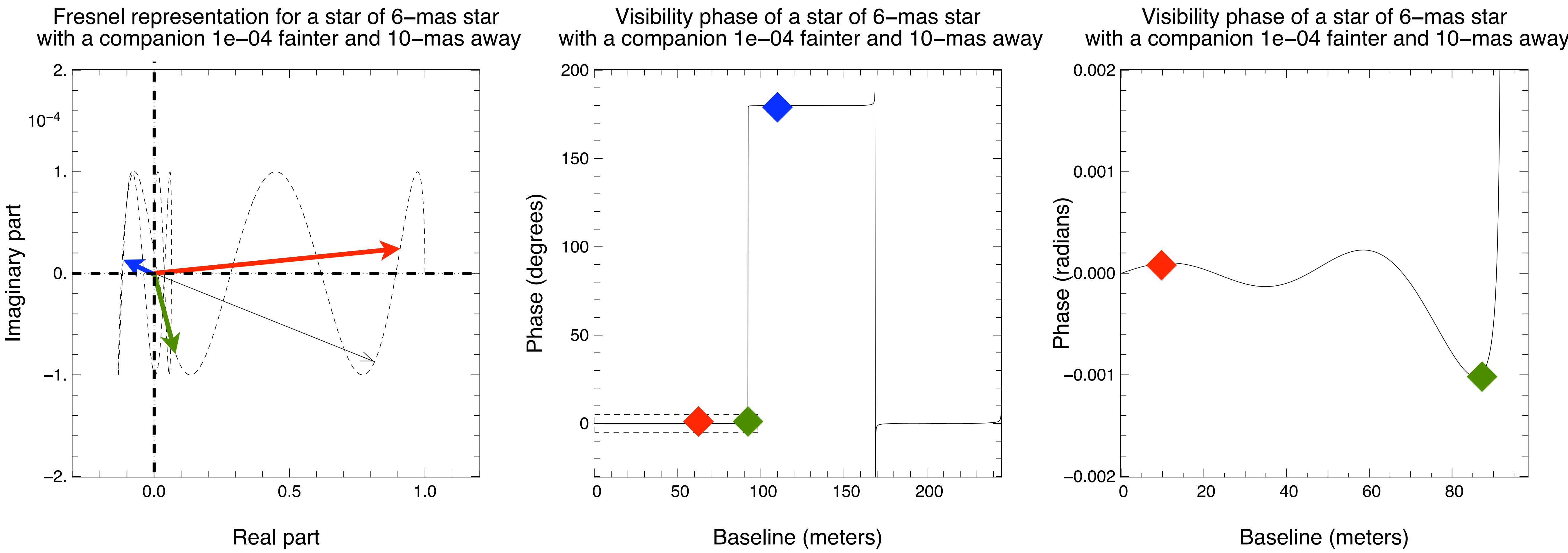
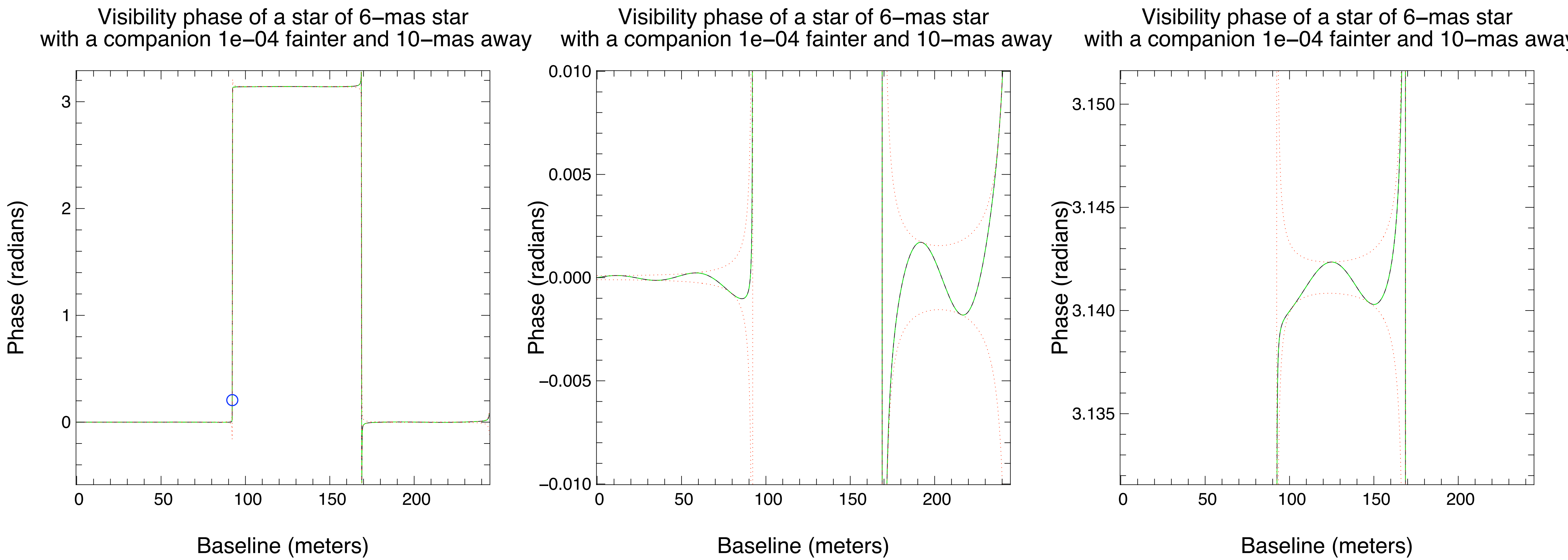


Phase of a faint companion near the null

$$\tan\phi(u) = \frac{r\,\sin(2\pi\,us)}{V_\star(B) + r\,\cos(2\pi\,us)}$$

$r \ll 1$

$$\phi(u) \approx \frac{r\,\sin(2\pi\,us)}{V_\star(u)} + n\pi$$



If $u=u_0$, $\Phi = 2\pi\, u_0 s$

Phase closure and closure phases

- Phase cannot be calibrated on ground interferometers because of the random atmospheric phase φ.

$$\Phi_{12} = (\varphi_1 - \varphi_2) + \Phi^o_{12}$$

- With 3 telescopes, it is possible to **close the phases**. on a triplet of telescopes.

- We use a variable, called the closure phase:

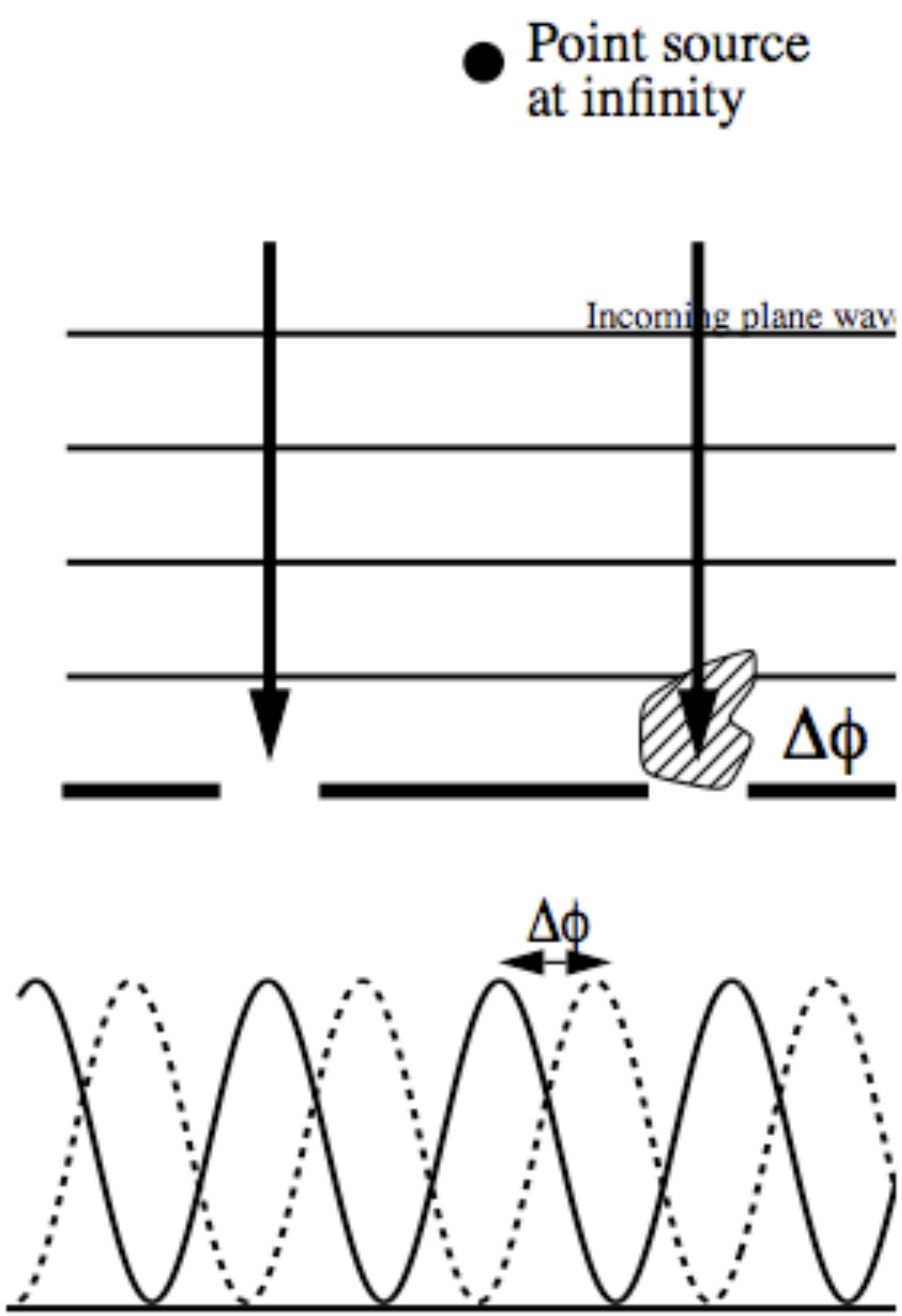
$$\Phi_c = \Phi_{12} + \Phi_{23} + \Phi_{31}$$

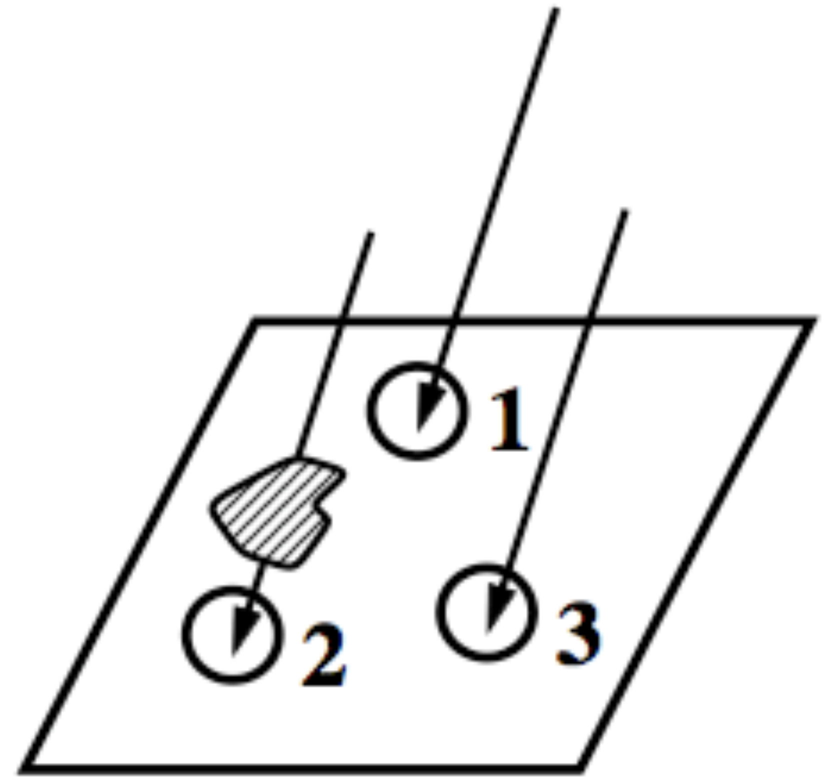
- The closure phase is independant of atmophere:

$$\Phi_c = \Phi^o_{12} + \Phi^o_{23} + \Phi^o_{31}$$

Phase closure principle

from Zhao et al. (SPIE 2008)



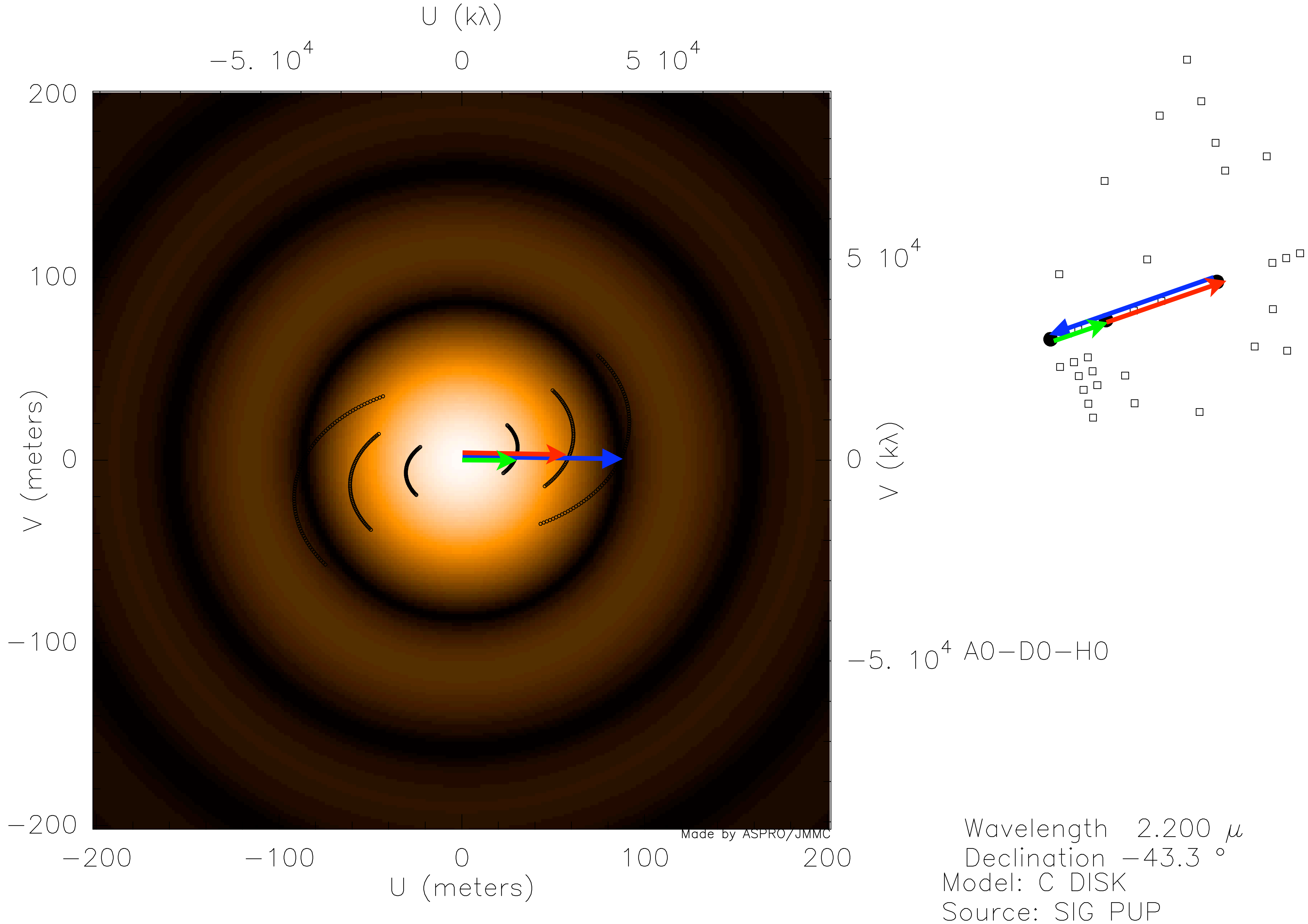


Observed | Intrinsic | Atmosphere

$$\Phi(1\text{-}2) = \Phi_o(1\text{-}2) + [\phi(2)-\phi(1)]$$
$$\Phi(2\text{-}3) = \Phi_o(2\text{-}3) + [\phi(3)-\phi(2)]$$
$$\Phi(3\text{-}1) = \Phi_o(3\text{-}1) + [\phi(1)-\phi(3)]$$

$$\boxed{\text{Closure Phase (1-2-3)} = \Phi_o(1\text{-}2)+\Phi_o(2\text{-}3)+\Phi_o(3\text{-}1)}$$

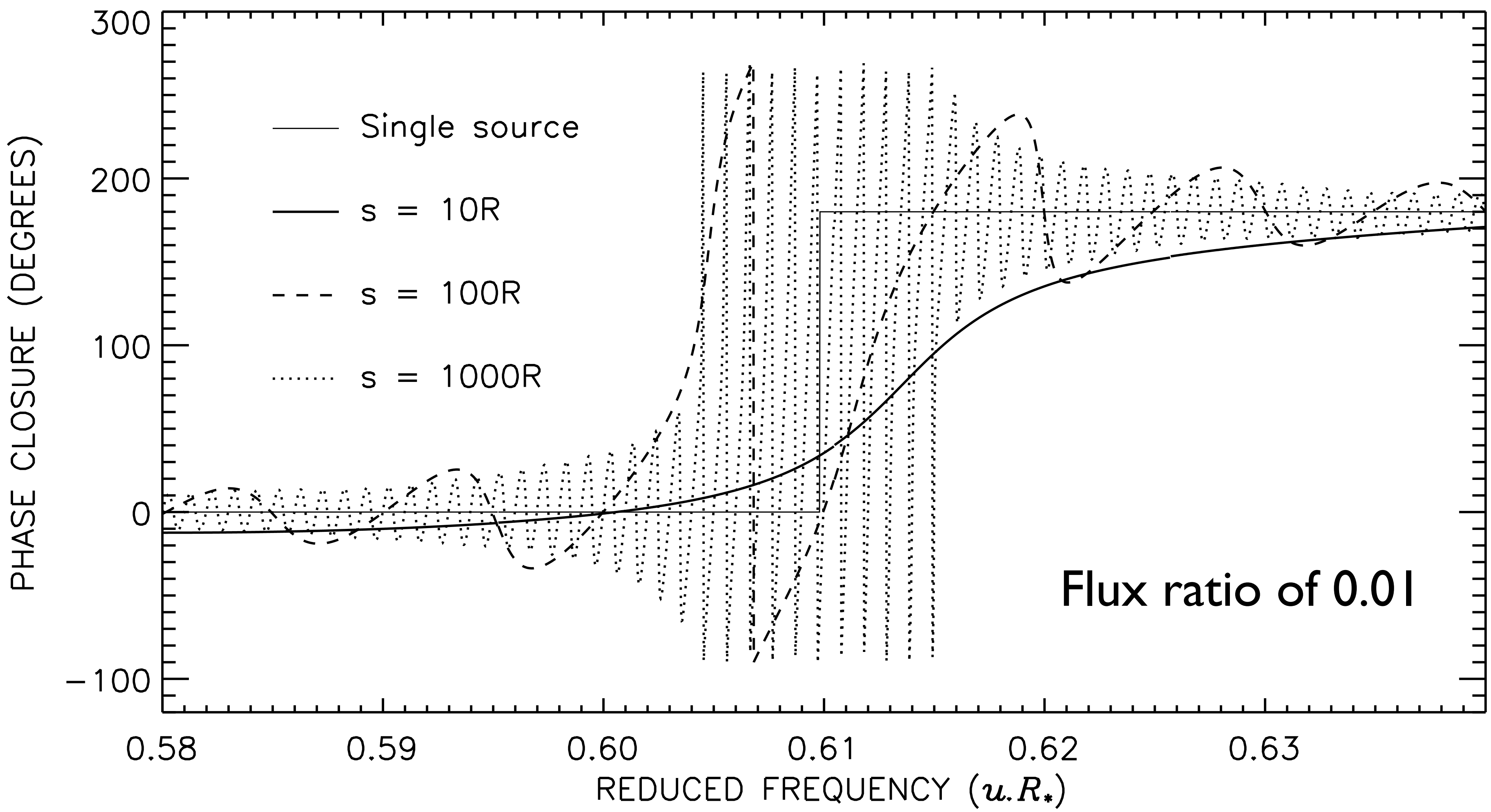
Closure phase near the null of σ Pup



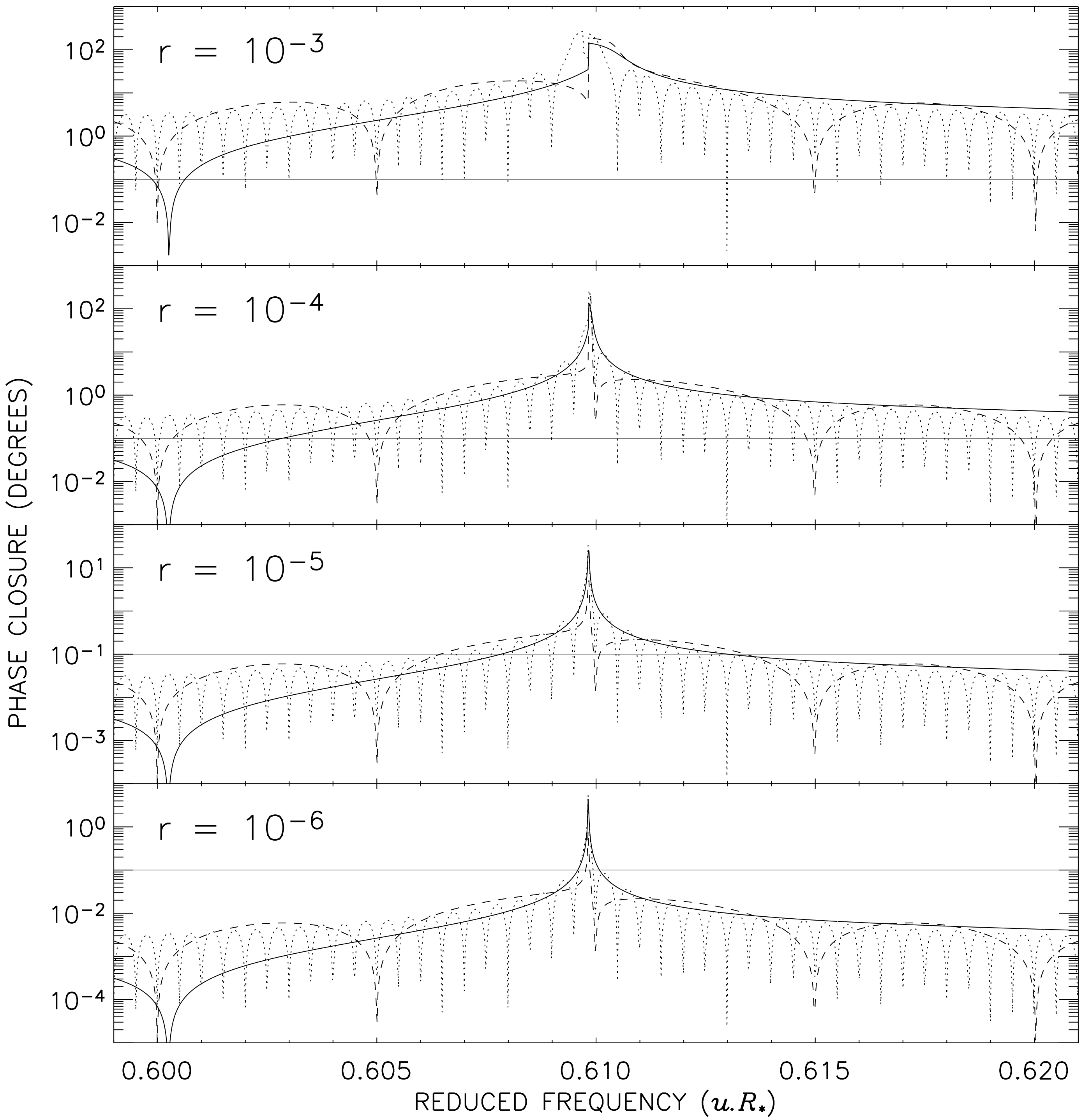
Closure phase near the null

$$\phi_c = \phi_o(u_{12}) + \phi_o(u_{23}) - \phi_o(u_{13})$$

$$\phi_c \approx \frac{r\,sin(2\pi u_{12} s)}{V_\star(u_{12})} + \frac{r\,sin(2\pi u_{23} s)}{V_\star(u_{23})} - \frac{r\,sin(2\pi u_{13} s)}{V_\star(u_{13})} + (n_{12} + n_{23} - n_{13})\pi$$

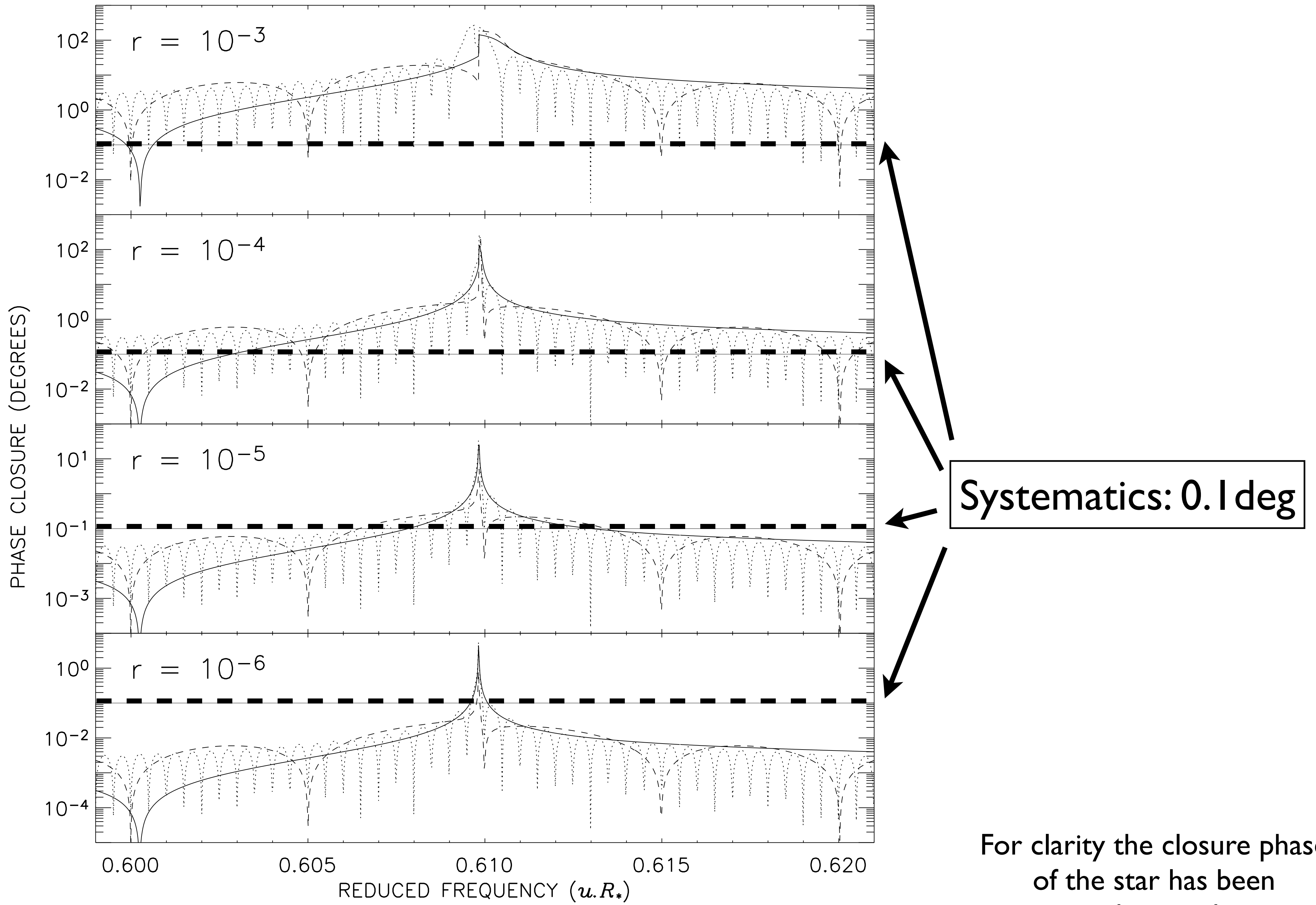


Various flux ratios



For clarity the closure phase of the star has been subtracted

Various flux ratios



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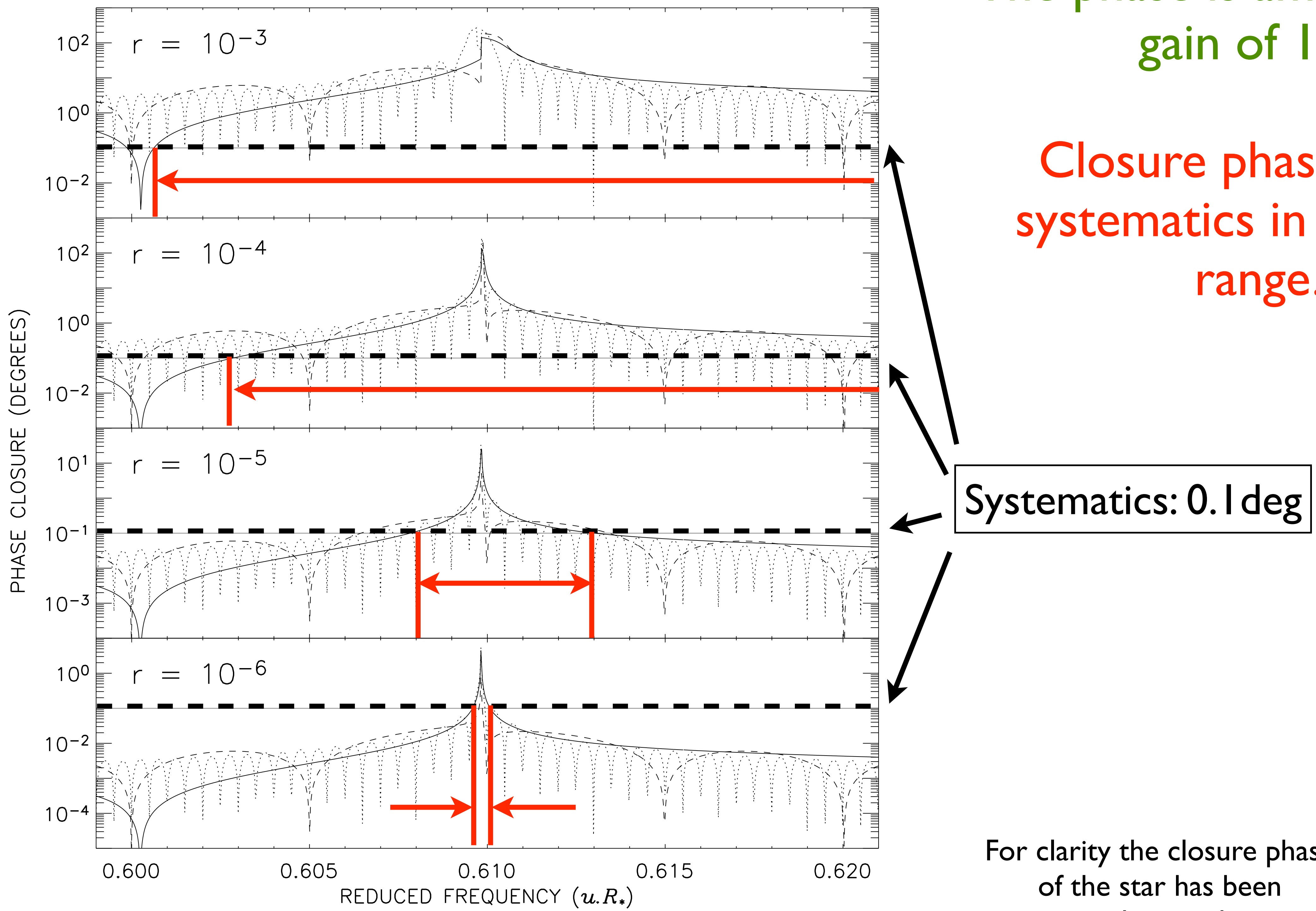


The phase is amplified by a gain of $1/V_*$

Closure phase above systematics in a limited range.

For clarity the closure phase of the star has been subtracted

Signal-to-noise ratios

- Neglecting the coupling between the photon noise and the detector noise and retaining the dominant terms, the variance of the phase closure is:

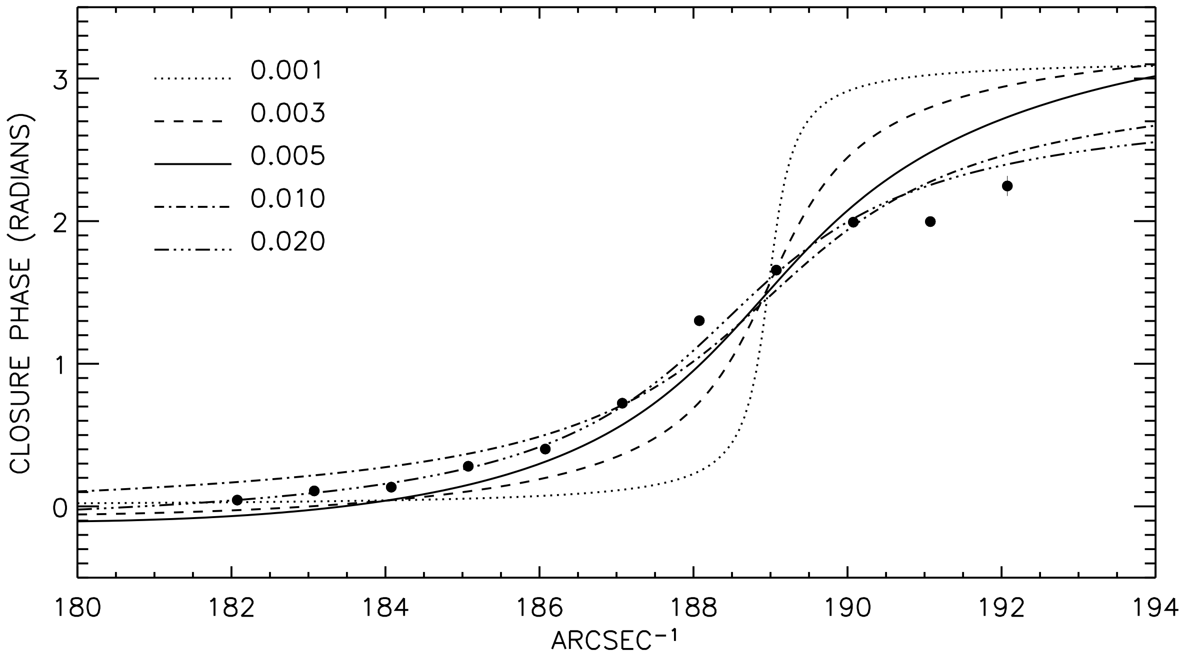
$$\sigma^2(\phi_c) \approx \frac{1}{2K}\left(1 + \frac{N_{pix}\sigma_r^2}{K}\right)\left(\frac{N_{tel}}{\rho_0 \bar{S}}\right)^2\left(1 + \frac{\sigma_S^2}{\bar{S}^2}\right) \times \left[\frac{1}{|V(u_{12})|^2} + \frac{1}{|V(u_{23})|^2} + \frac{1}{|V(u_{13})|^2}\right]$$

- The signal Φ_c being proportional to r/V_*, then there is no gain in SNR in the null. We still have to integrate enough to get the signal out of photon and detector noises.

How to retrieve the companion parameters?

- The double system is characterized by 4 parameters:
  - the stellar radius R_* ,
  - the flux ratio r between the star and the companion,
  - the separation s of the companion,
  - and the position angle PA.
- The 4 parameters may be extracted from a modeling of the closure phase variations as a function of both the spatial frequency and the wavelength.
- The spectrum of the companion is then obtained by multiplying the flux ratio by the spectrum of the primary.

The case of σ Pup



θ (mas)	*r*	*s* (mas)	*PA*
6.2-6.7	0.005-0.02	8.3 or 13.7	N/A

- Magnitude difference: Δm ~ 5 mag
- Only one baseline:
  - projected separation only
  - No position angle
- No measurements at null the 2nd night: no orbit motion

Literature data on σ Pup

- KIII spectral type
- Single lined spectroscopic binary (SB1) of P=257.8 days
- d = 56.3 pc, μ = 0.164 M_{sun}

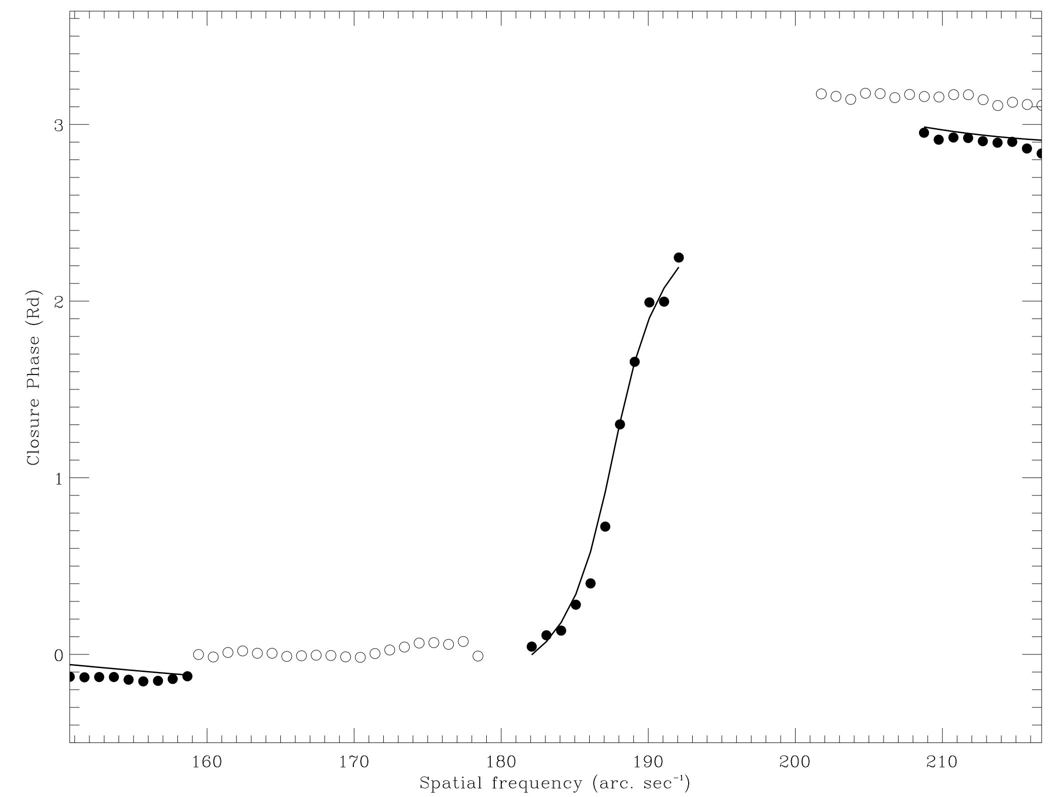


Table 3. Individual properties of the σ Puppis binary, and corresponding solutions for the orbit of the secondary. Columns are: Mass of Primary; Size of Primary; Mass of Secondary; Size of secondary; Spectral Type of Secondary; magnitude difference secondary minus primary; semi major axis of orbit of secondary; angular separation r_i and position angle ω_i for the two observation dates; variation in one day of the position.

M1 ($M_\odot$)	Φ_1 ($R_\odot$)	M2 ($M_\odot$)	Φ_2 ($R_\odot$)	Sp. Type (secondary)	Δ_{m_v} (mag)	a (mas)	a ($R_\odot$)	R^1_{roche} (mas)	r_1 (mas)	ω_1 (°)	r_2 (mas)	ω_2 (°)	Δ_{12} (mas)
5.0[a]	78	2.25	2.1[b]	A3 V[b]	1.9[b]	51.2	621	23.0	46.8	247.1	45.90	248.5	1.13
1.2[b]	78	1.024	1.0[b]	G2 V[b]	4.9[b]	15.7	224	6.15	14.3	247.1	14.05	248.5	0.35

[a] value from MSC catalog by Tokovinin (1997)
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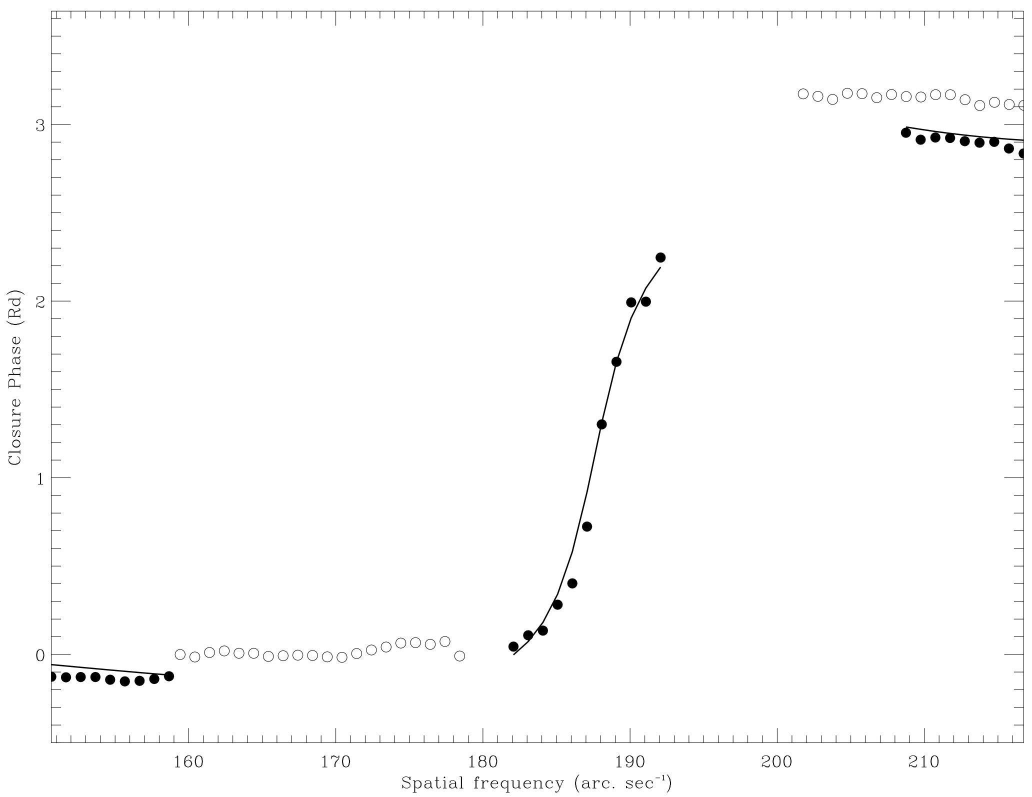

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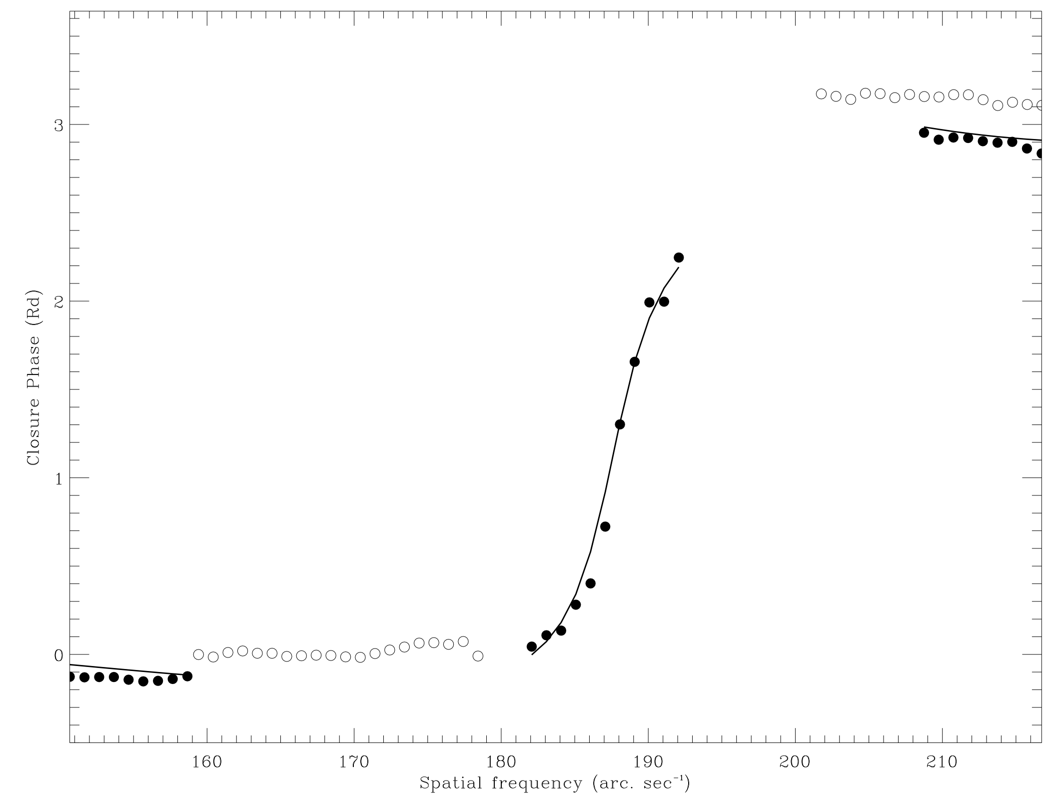

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Error analysis

$$\sigma(r) \approx \frac{3}{\rho_0\, \bar{S}\, \sqrt{K}}$$

$$\sigma(s/R_\star) \approx \frac{1}{r\, \rho_0\, \bar{S}\, \sqrt{K}} \left(\frac{0.61}{\bar{u}_{max}\, R_\star} \right)$$

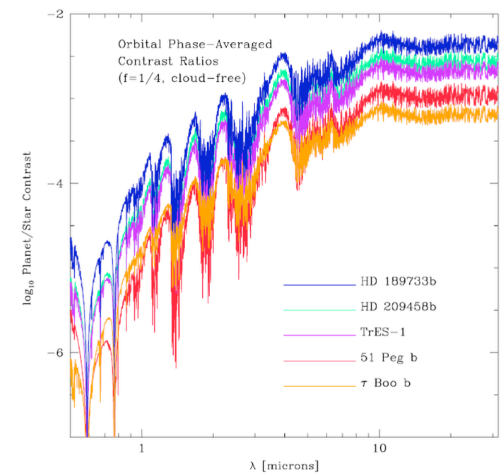
in the photon noise regime.

- formula valid even outside of the null
- independent of the spatial frequency u and the spectral resolution R
- $3/(\rho_0 S \sqrt{r})$ worse than direct detection for the companion flux rK

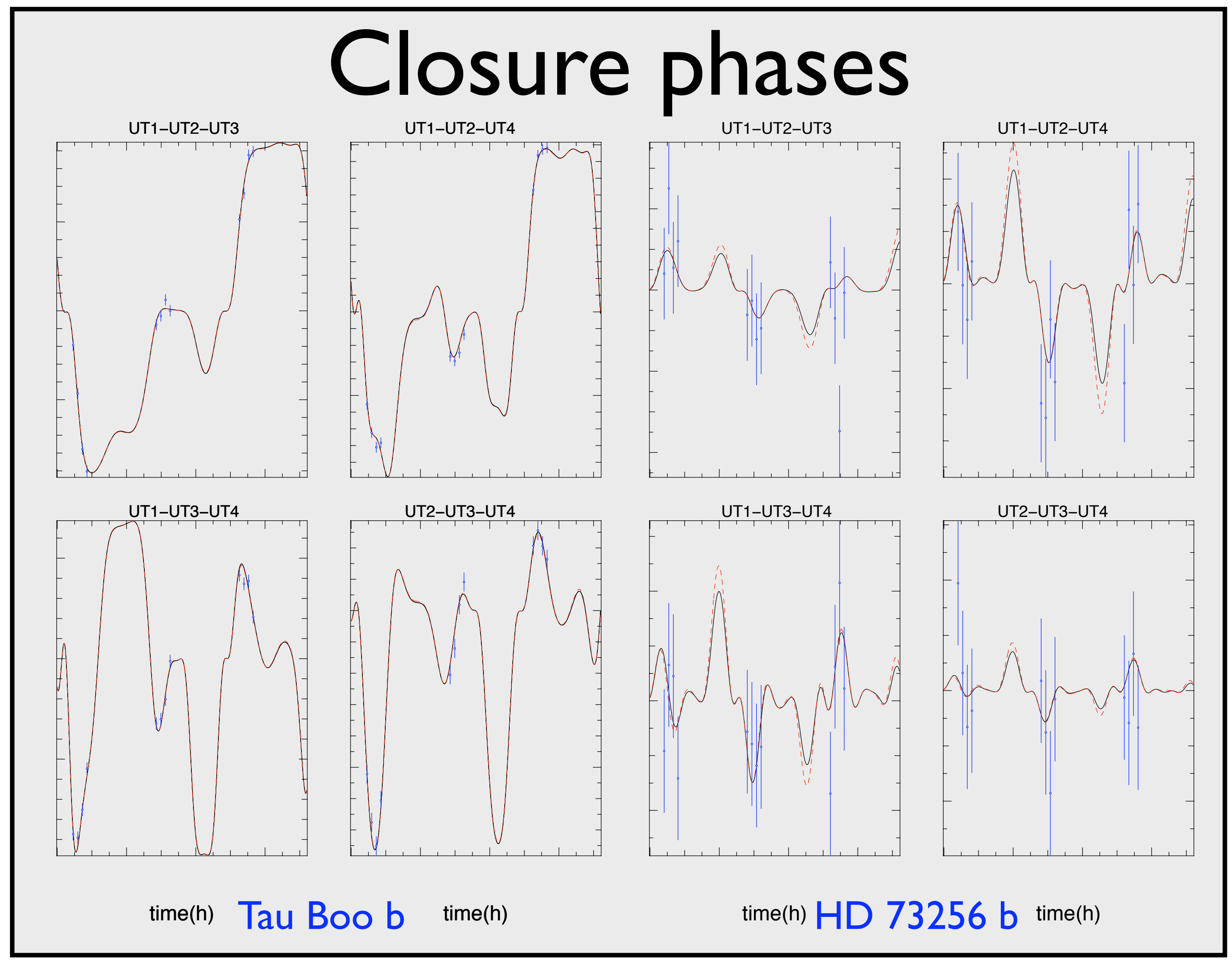
$$\sigma(rK) \approx \frac{3\sqrt{K}}{\rho_0 \bar{S}}$$

Detecting hot Jupiters with the VLTI

- Goal: to investigate the potentiality of the VLTI with 4 telescopes (VSI)
- to understand the limits of the phase closure technique
- to be able to propose an actual experiment with present instrument (AMBER)

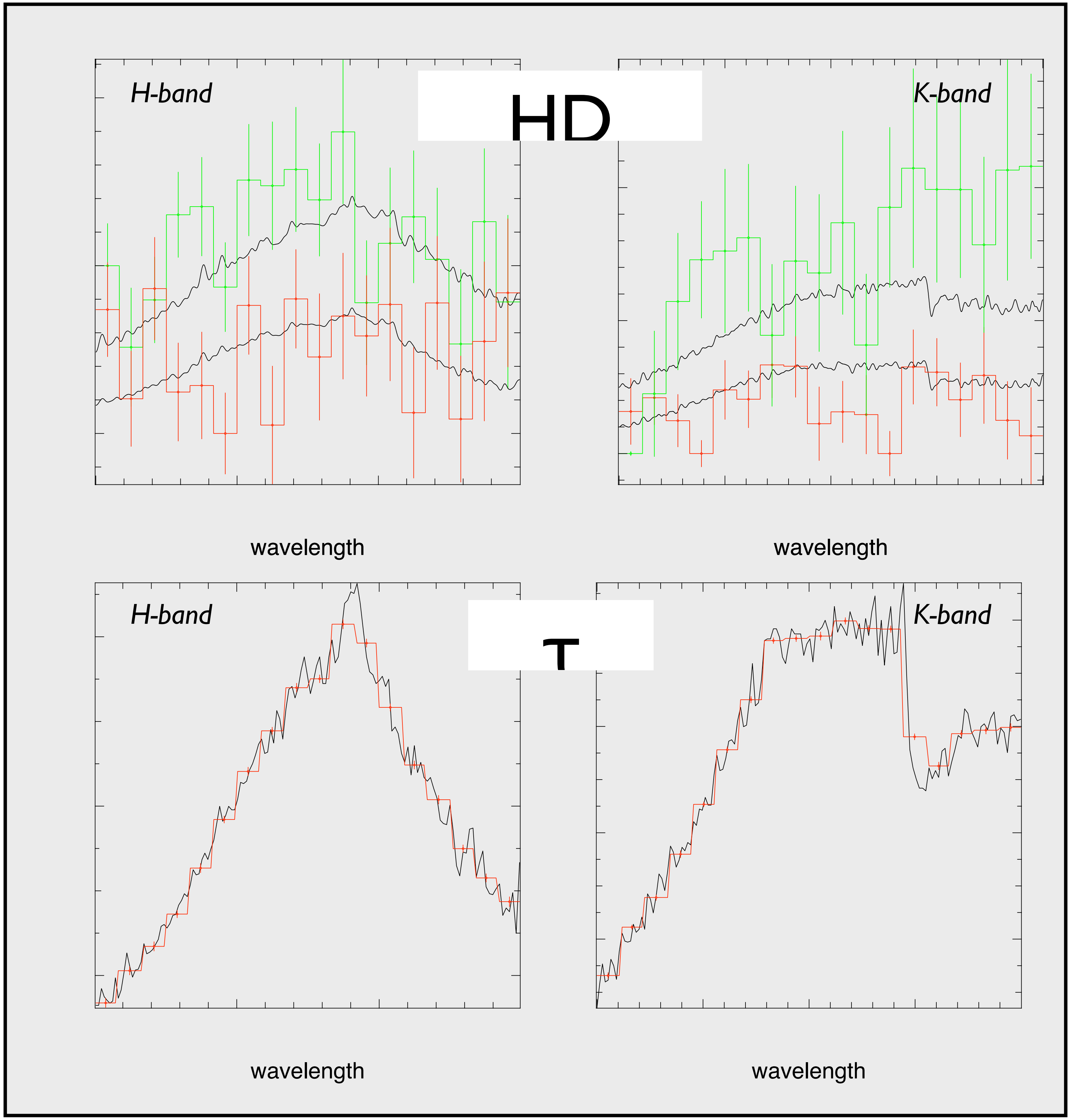


Synthetic spectra from Barman et al. (2001)



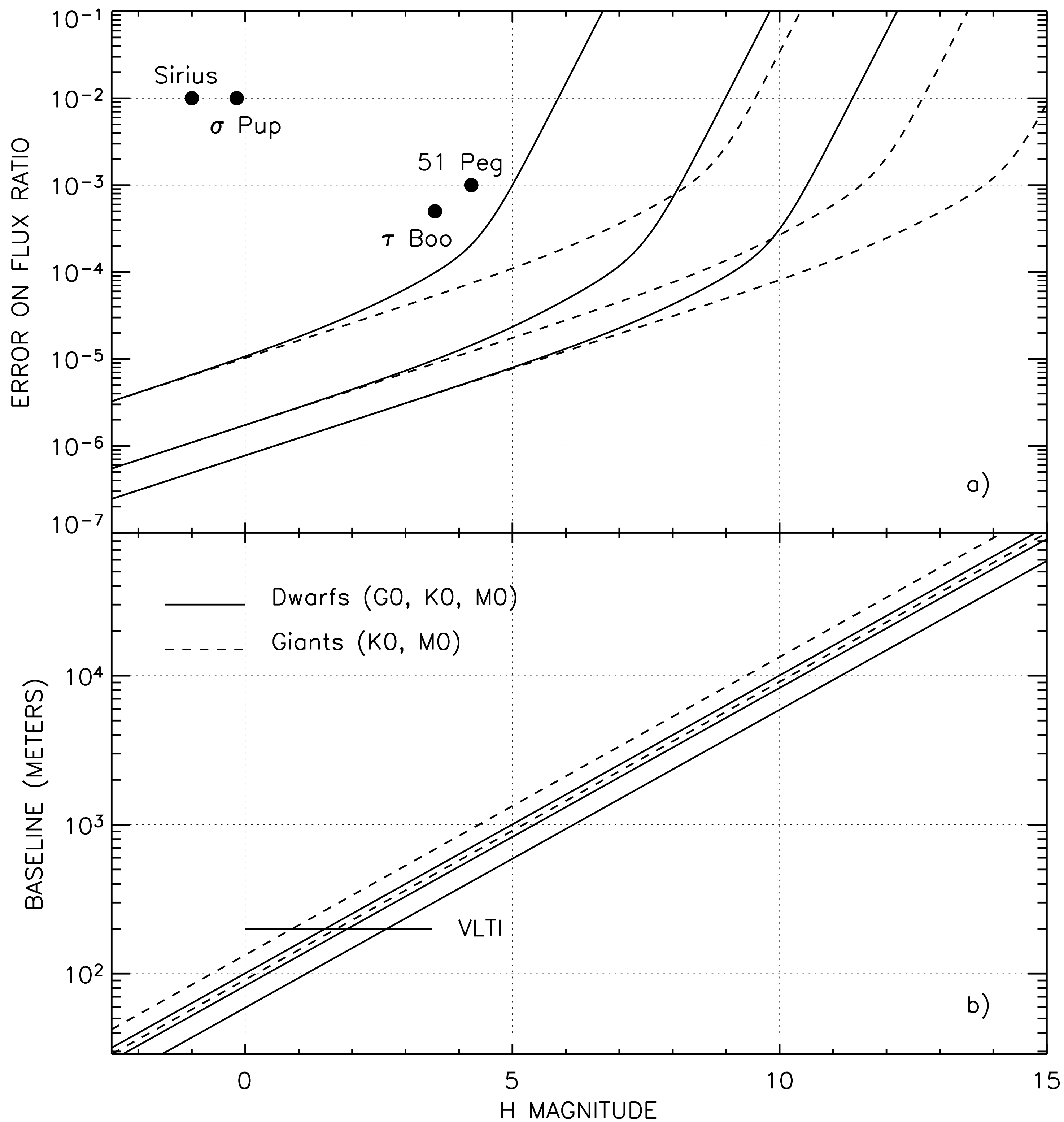
Renard, Absil, Berger et al. (SPIE 2008)

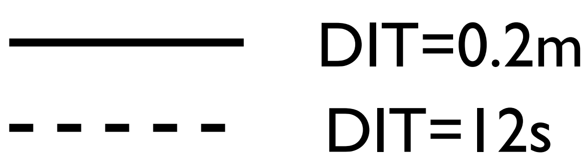
... can potentially lead to reconstructed planet spectra



Renard, Absil, Berger et al. (SPIE 2008)

Expected performances on actual stars





- R =1500 (270 channels)
- 900 CPs sampled regularly
- H band (1.65 μm)
- 3 hours of integration
- 3 scenarios:
  - D=2m, S=0.5, τ=1%
  - D=2m, S=0.9, τ=10%
  - D=8m, S=0.5, τ=10%

Already reached performances

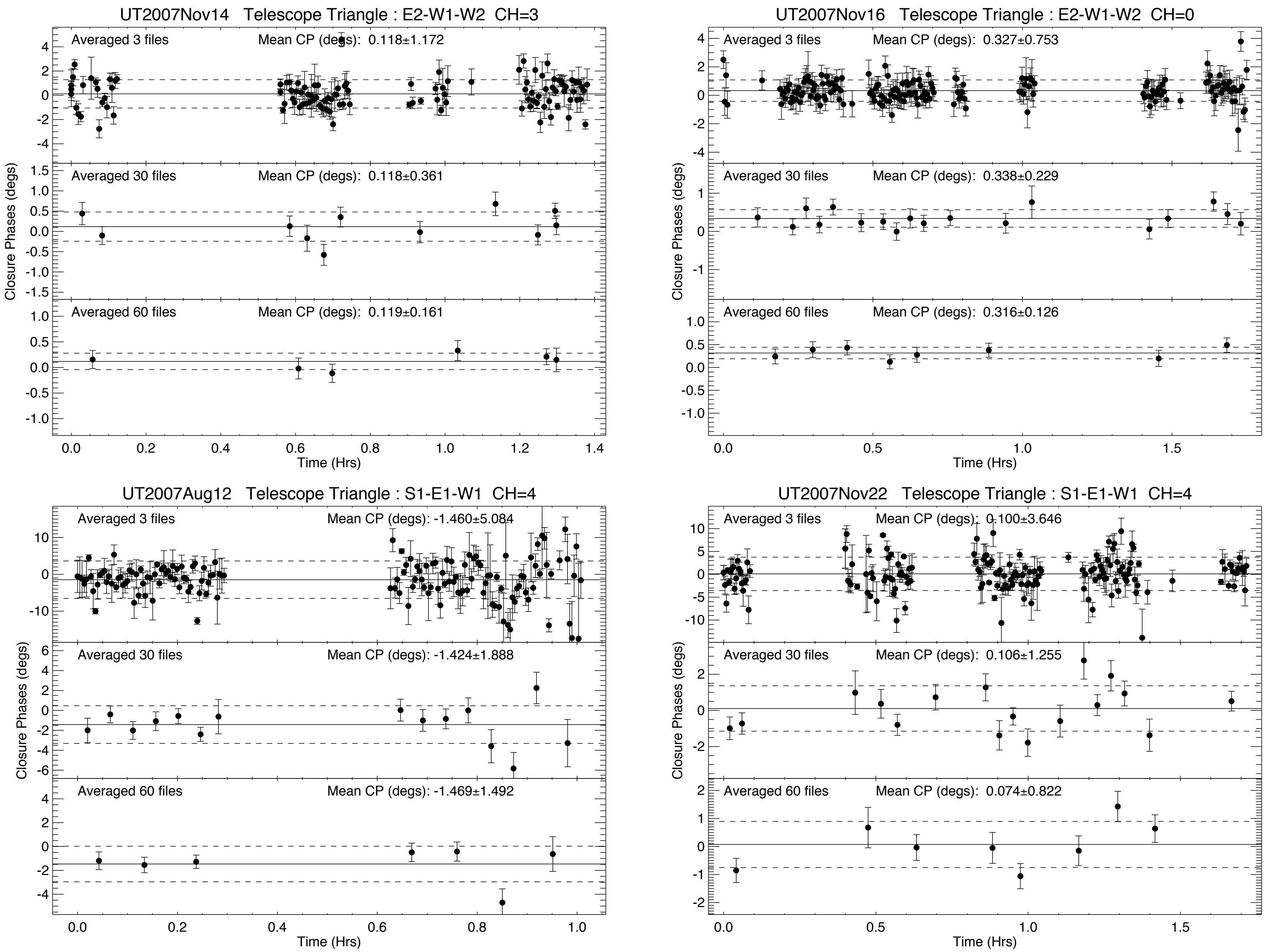


Figure 5. Preliminary results on υ And. Every single point in the top panel of each plot is an average of 3 files, corresponding to an integration time of 16 sec, while the points in the middle and bottom panel are average of 30 files and 60 files, corresponding to 160 sec and 320 sec of integration time respectively. The solid lines indicate the averaged closure phases for each panel, while the dashed lines indicate 1-σ deviation from the average. The top two plots show the results using the telescope triangle E2-W1-W2 which has a resolution of 0.7 mas. The bottom two show the results using the triangle S1-E1-W1 which has the highest resolution, 0.5 mas, among all the baselines of CHARA. MIRC wavelength channel numbers are indicated at the top of each plot. Channel 0, 3, 4 correspond to 1.76μm, 1.66 μm, and 1.63 μm, respectively.

Zhao et al. (SPIE 2008)

Other topics

- Number of stars accessible
  - 100 in K for VLTI
  - 500 in J for VLTI
- Planet, wave, wind signatures in protoplanetary disks
- Cataclismic variables
- Active galactic nuclei
- Protoplanetary nebulae
- disk around hot stars
- companion of evolved stars
- companion of MS stars

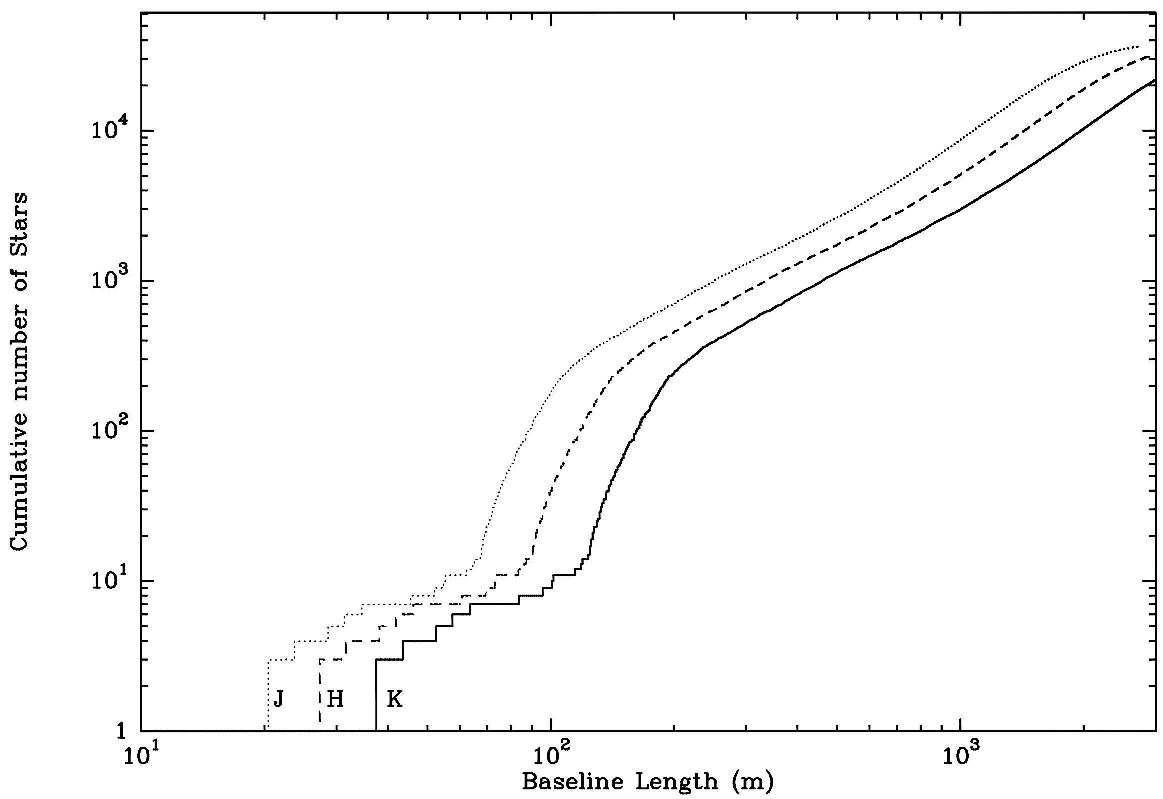


Fig. 5. Cumulative number of stars resolved at a given baseline in the J, H and K bands. The sample has been obtained with the SearchCal utility (Bonneau et al. 2006) and is limited to the stars whose apparent diameter can be reliably estimated from parallax and (spectro)photometric measurements available at CDS. Note that these numbers are lower limits given the uncompleteness of the various catalogs used.